Title
PROBLEMS AND TECHNIQUES IN THE ANALYSIS OP BUBBLE CHAMBER PHOTOGRAPHS

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Hugh Bradner

January 29, 1960

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The three parallel sessions of invited papers this morning lead me to expect a greater-than-usual fraction of active Bubble-chamber physicists in the audience. Therefore I hope that you will permit me to spend a disproportionate time talking about problems that need solution ... And forgive me if I make much use of a crystal ball concerning the future. It will be a talk on apparatus, rather than physics.

The task will summarize what we have accomplished and learned in the field; and what some future developments may be in data reduction for bubble chambers. "We" refers not just to Berkeley, but to Brookhaven people such as Thorndyke and Fowler and Rau; to Goldschmidt-Clermont at Geneva; to Hough at Michigan; to Glaser; and others.

The specific bubble-chamber data that I cite refer to the Hydrogen Bubble Chamber operations at Berkeley, since I am most familiar with them.

Shutt's group at Brookhaven may have been the first to realize the magnitude of the data-reduction problem. Well-established cloud chamber techniques could analyze about one event per day. That was all right, since interesting events were then photographed about once per day. Shutt's group built a 16-inch-diameter 20-atmosphere hydrogen diffusion chamber to study the three or four strange-particle events that they would get among the 200 events (at 35 mb cross section) from 5,000 pictures per day at the Cosmotron. They could scan only 100 to 300 pictures per man-day, and required about 5-man-days to analyze each day's events. They started to consider ways of speeding up the scanning and analyzing.

When Dr. Alvarez proposed making a 72-inch liquid hydrogen bubble chamber, which would have an effective density of 1,000 atmospheres, the crisis was obvious. Besides, the Bevatron was expected to give us 10,000 pictures per day! That would produce 1,000 strange-particle events per day.

Those early estimates of running efficiency were too high. We averaged somewhat less than 3,000 pictures per day with the 15-inch chamber last year, and only about 1,000 pictures per day with the 72-inch chamber in the 4-month antiproton run last fall. It now seems that we will have 70,000 to 100,000 strange-particle events per year in the 72-inch chamber. Our analysis system is working well for the 15-inch chamber; but Dr. Button's talk this afternoon

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on the $\bar{p}$ experiment (the first physics run in the 72-inch chamber, by the way), will show you that the 72-inch analysis is slow in starting.

It must get up to full speed quickly, because a 5-month run, scheduled to start within two months for Dr. Frank Crawford, is expected to produce about 600,000 pictures, with 75,000 lambdas, 200 lambda scatterings on hydrogen, 40 beta decays of lambdas, and many other interactions, including 50,000 π-π events, plus four million ordinary interactions that we won't attempt to analyze.

When the bubble chamber effort began, Dr. Alvarez's group in Berkeley was interested only in strange-particle interactions, so that our task was to develop a system that could handle events 300 times as fast as cloud-chamber techniques. We expected that measuring the pictures would be the bottleneck.

The analysis of bubble chamber events requires three-dimensional reconstruction of the trajectory of all particles involved, followed by a computation of momentum balance and energy balance. Stereophotography by two camera lenses is sufficient to permit this reconstruction, but a third lens is added because it speeds up measurement. The photographs contain other information besides the direction of the tracks: The curvature of the track in the magnetic field is a measure of momentum divided by charge; the direction of the curvature indicates the sign of the charge; the number of bubbles per unit length is a function of the velocity of the particle and of its charge; the range of a particle that stops in the liquid gives the momentum, if the particle mass is known; the change of curvature with distance can establish mass if measurements are sufficiently accurate, and if multiple Coulomb scattering is small enough. Energetic delta rays can give some information on the velocity of the particle.

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The frequent appearance of inelastic processes in high-energy physics usually demands that the trajectories of the particles be reconstructed with the highest possible accuracy. The geometrical problems of reconstructing an event in a bubble chamber are similar to the problems encountered in the analysis of cloud chamber photographs, but the problem is more difficult. The reconstruction is complicated by the fact that the liquid has an index of refraction differing from unity; camera optics are usually wide-angle, and therefore corrections for the chamber windows are nonlinear; the magnetic fields in some chambers are very nonuniform.

These considerations led Dr. Alvarez to propose that we make coordinate measurements independently on the different stereo views, and then make geometrical reconstruction, along with optical and magnetic corrections, in a digital computer.

The system that has evolved consists of the following steps, requiring the times indicated in the boxes.

1. Search for events

10 min per event for each scan*

Physicists and technicians search for events of interest, and tabulate what they find, then rescan to learn the percent of events overlooked.

The scanning machine is shown in Fig. 1. In this machine the three images are projected onto a white bakelite surface at a magnification of 10 diameters, i.e., 2/3 original bubble chamber size. The projection lenses are Schneider Companon 210 mm focal length at f/5.6. It was necessary to use high-quality wide-angle lenses, because the optical rays can make a maximum angle of 35 deg from optical axis. The mirrors are paralleloplate, front surface aluminized and silicon monoxide coated. The paralleloplate and a special mounting suspension were required to keep the magnification sufficiently uniform throughout the picture. Illumination is by means of three 500-watt motion picture projector lamps operating with f/0.8 lucite condensers and Corning I-58 and I-69 heat-absorbing glasses. Film is clamped in an open-faced holder. Temperature rise, measured on a black piece of film, is no greater than 3° C.

We usually find it desirable to scan along the track, i.e., from the end of the table. It was not possible to magnify the image enough to see the necessary detail at the near end of the image without having the far end too distant from the observer. Hence, the film carriage was arranged to roll easily and thereby move the image toward or away from the operator by means of a hand lever.

The film can be advanced from one frame to the next in approximately 3/4 sec. It can be run at slow speed of 800 ft/min and can be started and stopped with a maximum force of less than 3 pounds on the film.

These machines cost approximately $12,000 each. They may cost as much as $20,000 with further automatic controls. This seems like a large sum, but we should realize that running the Bevatron and the bubble chamber for one day costs between $12,000 and $20,000.

2. "Sketch"

10 min/event

Physicists or very experienced assistants examine each event, list possible interpretations, and write instructions to the measurer and to the computing program. This is done on a scanning table. The time required is about 10 minutes per event. (More accurate figures are available from time-and-motion studies if you are interested.)

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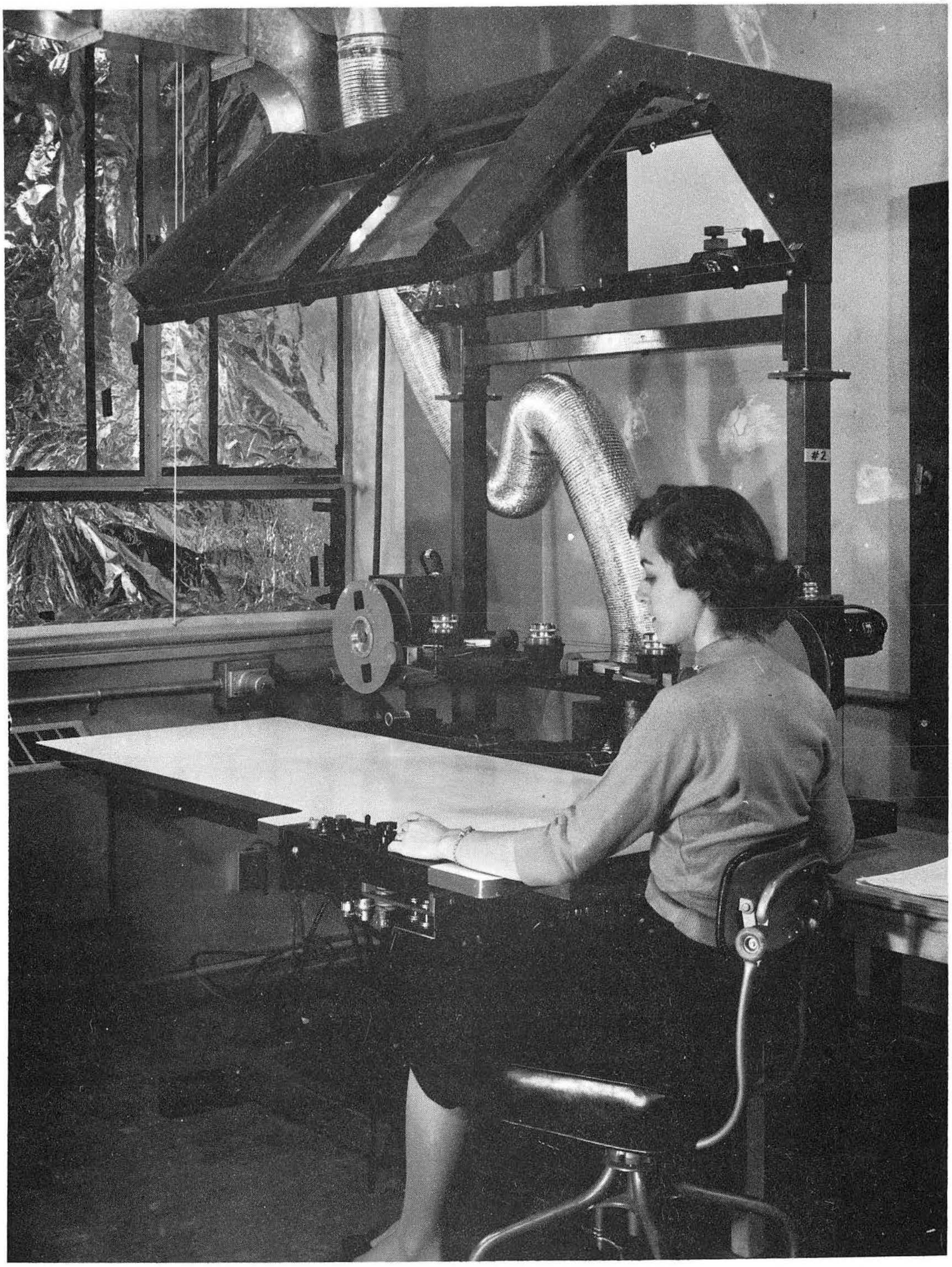

ZN-2341

Fig. 1

3. Measure

10 min/event

Technicians measure films on "Franckenstein." Many of you are familiar with the Franckenstein measuring projector for the smaller chambers. Figure 2 shows the machine used for 72-inch chamber film. A second one is being built now at Berkeley.

The characteristics of the projection microscope do not differ greatly from the Franckenstein for the smaller machine. It, too, is accurate enough that measurements may eventually be limited by uncertainty due to multiple Coulomb scattering. Measurements are made on axes, to 2.5 microns accuracy, by using Ferranti moiré fringe grating systems. The automatic track-following servo is the same as on the smaller machine: the image is sampled via 24 slots on a 3600-rpm motor (i.e., a rate of 1440 cycles per second). The big difference between the two machines is brought about by the large image on the film. It is necessary to magnify the image to approximately 2.2 times actual size in order that an operator can make visual settings on fiducial marks and track endings to the necessary accuracy. We did not see any satisfactory way of presenting a picture 14 feet long, so we split the image. The region being examined in detail is projected by a Schneider Xenotar f/2.8 lens of 10.5 mm at a magnification of 33, to give the 2.2-times-full-size image on a transmission screen. A partially silvered mirror projects a second image through a Dallmeyer Serrac f/4.5 lens, of 18-inch focal length, at a magnification of 7.5, i.e., one-half life size, onto an opaque screen. An illuminated reticle projected onto the half-scale view shows the region that is enlarged to 2.2 diameters.

A detail of the lamp housing, the condensers, and the film carriers of the measuring machine is shown in Fig. 3. It was necessary to use a 2500-watt mercury lamp of 120,000 lumens output to get the light that was needed while simultaneously presenting the split images and servo-system photomultiplier. In addition, aspheric lucite condensers are used to give high illumination over the entire film. Heat-absorbing glass and water cells are required to keep the film cool.

The same film transport is used as on the scanning machines.

The first measuring projector cost nearly $200,000; the second, which is now under construction, will cost about $140,000.

4. Compute

computing 1/2 min per event
plus handling 1/2 min/event

The output perforated tape with x-y coordinates of track segments and fiducial marks (chamber glass) is converted to magnetic tape, and put into an IBM 704.

The 16,000-word program reconstructs the event completely, with momentum and energy balance. It prints out lab and c.m. components of momentum, energy, and angles, together with propagated errors and goodness or fit. Right now, 15,000 events are waiting some minor program revisions for the new 704.

ZN-2342

Fig. 2

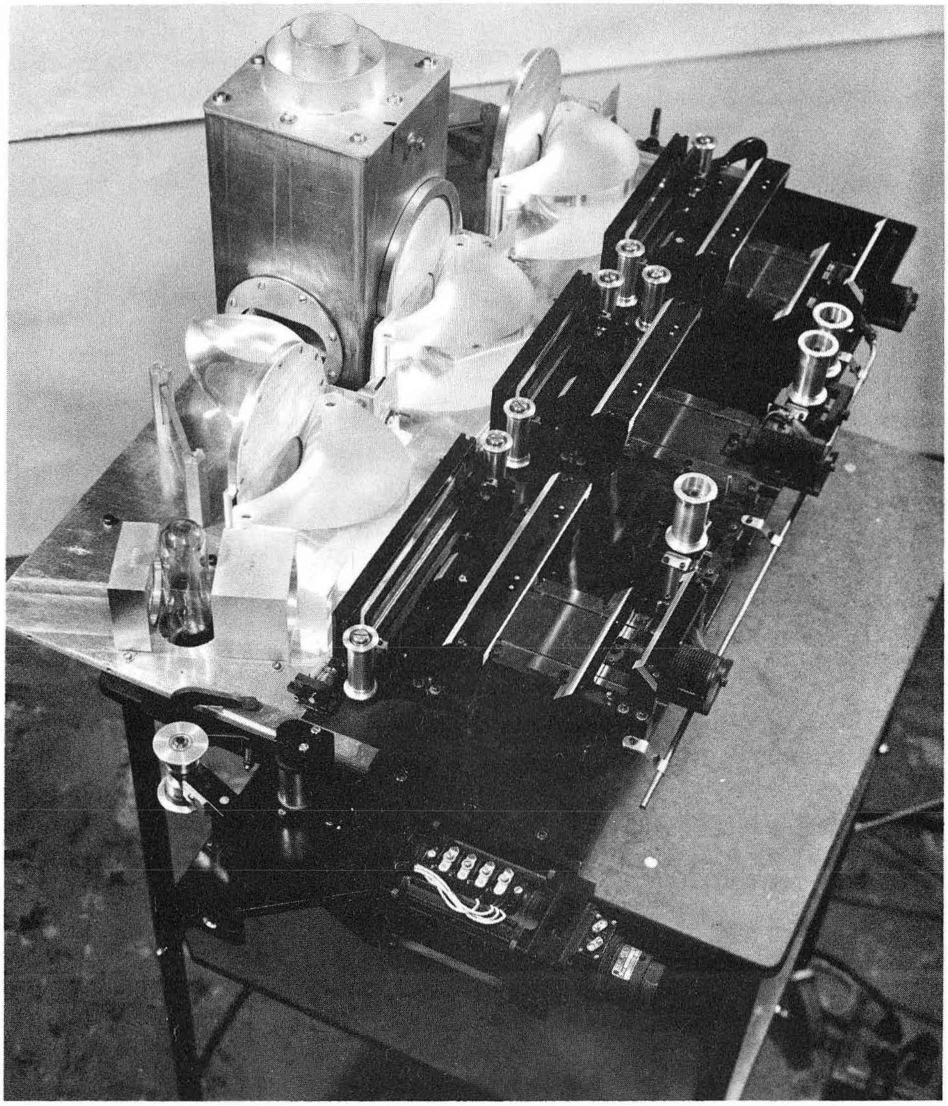

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Fig. 3

5. Examine

2 to 30 min/event

Not all the events go through the computation successfully. Errors in "sketching" or in Franckenstein measurement cause 5 to 10% of the events to fail on a well-debugged program. The failure rate during the first six months of a new program is often 30%. Events that fail are re-examined and rerun. This is a less efficient procedure than the routine first analysis, because of the time spent in understanding the error, and in looking up old records and old film. Examination and rerun averages perhaps 6 minutes per event. A year ago, when 30% of the events were failing, it was even more; this was the bottleneck, rather than measuring.

6. Sort

The "good" outputs are correlated and tabulated, for angular distribution, up-down asymmetry, etc., as required for the physics of the experiment. Groups at other laboratories have developed better programs for these operations than we in Alvarez's group, to date. We still do most of it at a desk.

7. Keep Records

6 min/event

The tabulations of events found in scanning must be correlated, and the records must be kept for reference. The "sketch cards," which now are 8-1/2 × 11 McBee Keysort cards, must be filed, as well as the printouts from the computer. All this is being done now by one extremely good person, plus the physicists as they use the data. But it is a cumulative job which will need to be mechanized soon. We have looked briefly into normal actuarial and business methods. IBM Ramac does not meet all our needs. Perhaps we can use some new library sorting and recall techniques, such as ITEK is developing.

The times for these operations seem fairly well balanced. Three or four scanning machines and one Franckenstein can process 20,000 event per year. Actually, we did 10,000 events from the 15-inch chamber during 4 months last year with four scanners and two Franckensteins. The Franckensteins were not fully scheduled on week ends.

About 2 minutes can be saved in all the bottleneck operations by putting automatic frame selection on scanners and Franckensteins, and by improving the interlocks that force the operator to make all measurements in the correct order. These things are being built. Automatic transfer of the physicist's instructions from the sketch to the Franckenstein and the computer will be done later if it seems necessary.

Experience with the 72-inch film is brief, and may give some surprises. Scanning per picture is certainly slower. To a first approximation, we find that it takes four times as long per picture, since the eye can see only a limited area at a glance. We find that we can stand only the same number of tracks per picture (20 or 30) without confusion or ambiguity. Hence, the scanning time per interaction is about the same as in the smaller chambers.

It would appear that the Franckenstein system can be made to handle 70,000 to 100,000 strange particle events per year, by using three or four measuring machines, 12 to 15 scanning machines, and a staff of about 50 technicians. About five full-time physicists will be needed for the analysis--not including programming.

Recently it has become clear that the non-strange-particle interactions are a very important field of investigation in fundamental nuclear physics. Some excellent theorists feel, in fact, that the study of these interactions is now of greater importance than the strange particles. It seems necessary to measure a very large number of events in order to extrapolate with the necessary statistical accuracy into the nonphysical region that is of major concern to the men working in dispersion theory. And in most cases it seems necessary to measure the events to the same high accuracy required for strange-particle studies. The hydrogen bubble chamber seems to be the most powerful tool at the present time for such investigations, because of the large number of interaction types that can appear, and the angular momentum and accuracy required.

So now, we are faced with the problem of analyzing several million events per year. It is obvious that the Franckenstein system cannot be extended to cope with the job. Even I shudder at the idea of 50 measuring machines and 30 to 50 scanning machines grinding away on the film from a single bubble chamber run.

It does not seem reasonable for physicists or technicians to examine the necessary number of pictures, or to enter any appreciable amount of data for a measuring machine at the necessary rate, or to examine the output of the computing machine in detail for each event. We would need to look at one output per second during a normal working year.

Evidently, if we are going to accomplish this task, we must find a way of using a machine to locate the events of interest--a frightening prospect but I do not see any alternative. We must also measure these events automatically, and record and tabulate only those events which have satisfied our initial criteria. We must, of course, be very careful that the events we discard are randomly distributed--the better our statistical accuracy, the smaller systematic error we can tolerate.

The problem of recognizing events automatically is not trivial. In fact, I don't think it has ever been done, with the possible exception of some pioneer work by P. V. C. Hough at Michigan. The task appears less formidable than some of the jobs being undertaken in translation, deciphering of handwriting, or recognition of patterns in aerial photography. It would certainly be necessary to have a large computer attached directly to the apparatus. It may be necessary to design a special computer. The same computer would direct the measuring machine and carry out the analysis of events after they are measured. The computer programs would be very complex.

The problem of making a measuring machine with the required speed and accuracy is a big one, but Bruce McCormick, an extremely capable man, has been working on it for a long time. (He is probably the first man to tackle this job of ultra-high-speed analysis). His mechanical flying-spot machine--called, of course, the "McCormick Reaper" is shown in Fig. 4 as it looked in mid-January. This is a front view of the console with the film transport, which is a modified Ampex tape drive to present the section of the film on which measurements are to be made. An enlarged image of the film is displayed on the transmission screen at the center of the console. The two wings of the console are now filled with indicator lights and control switches. The stage carrying the lens and light system has been removed for this photograph and the next.

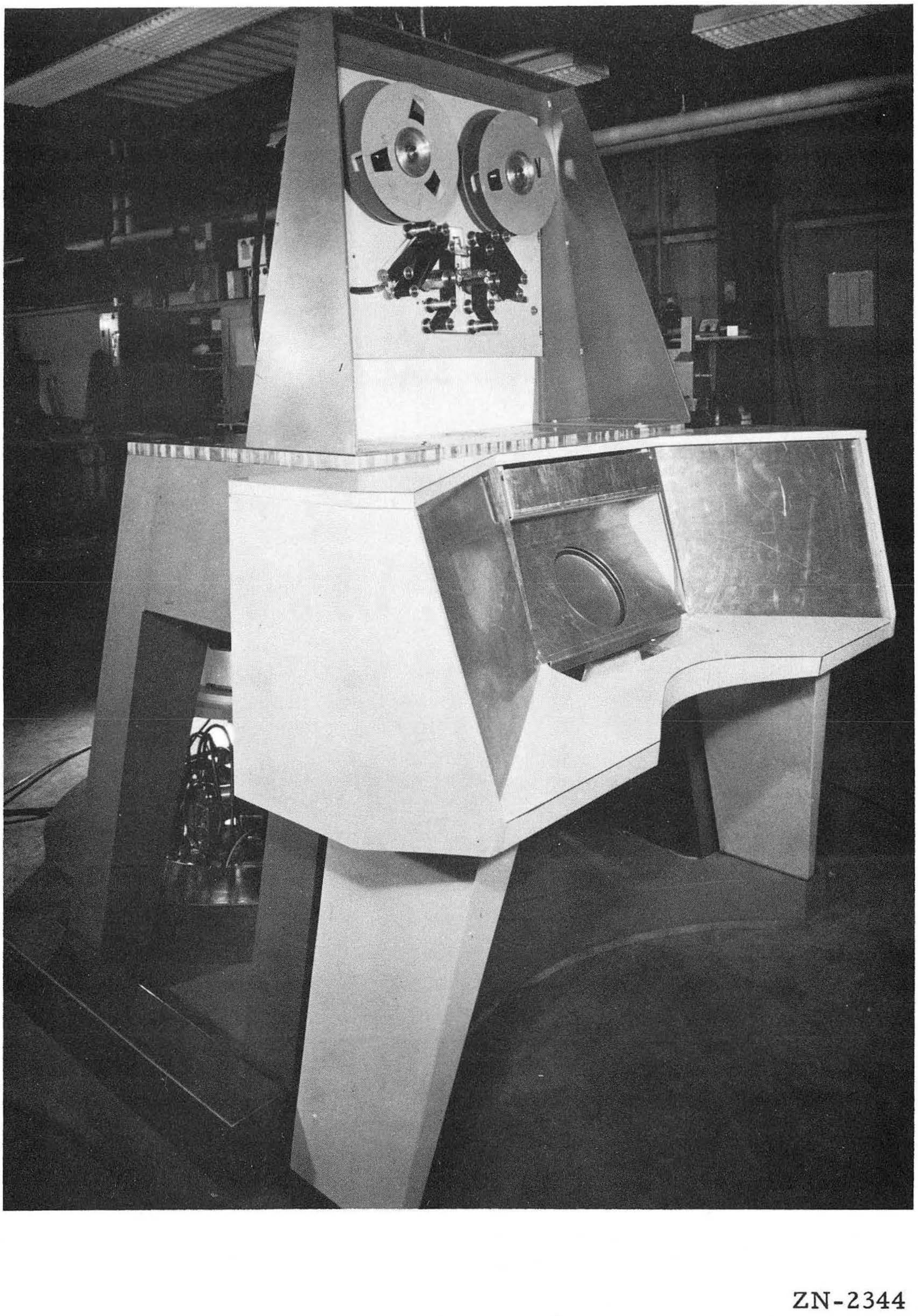

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Fig. 4

The rear view of the console is shown in Fig. 5. In the foreground is the rotating drum surrounding the slit plate, the Baldwin disk with 2^{16} bits on its outer ring for defining the angular position of the slitted disk, and a system of light pipes carrying the signals from the slits down to the photomultipliers.

The racks to house the transistorized electronics for the controls and some of the computer components are seen in Fig. 6. More than 10% of these racks have been filled since this picture was taken.

(A television flying-spot tube of 50,000-line resolution would be needed to scan an entire picture with the necessary resolution. Trickery may make it possible with less.)

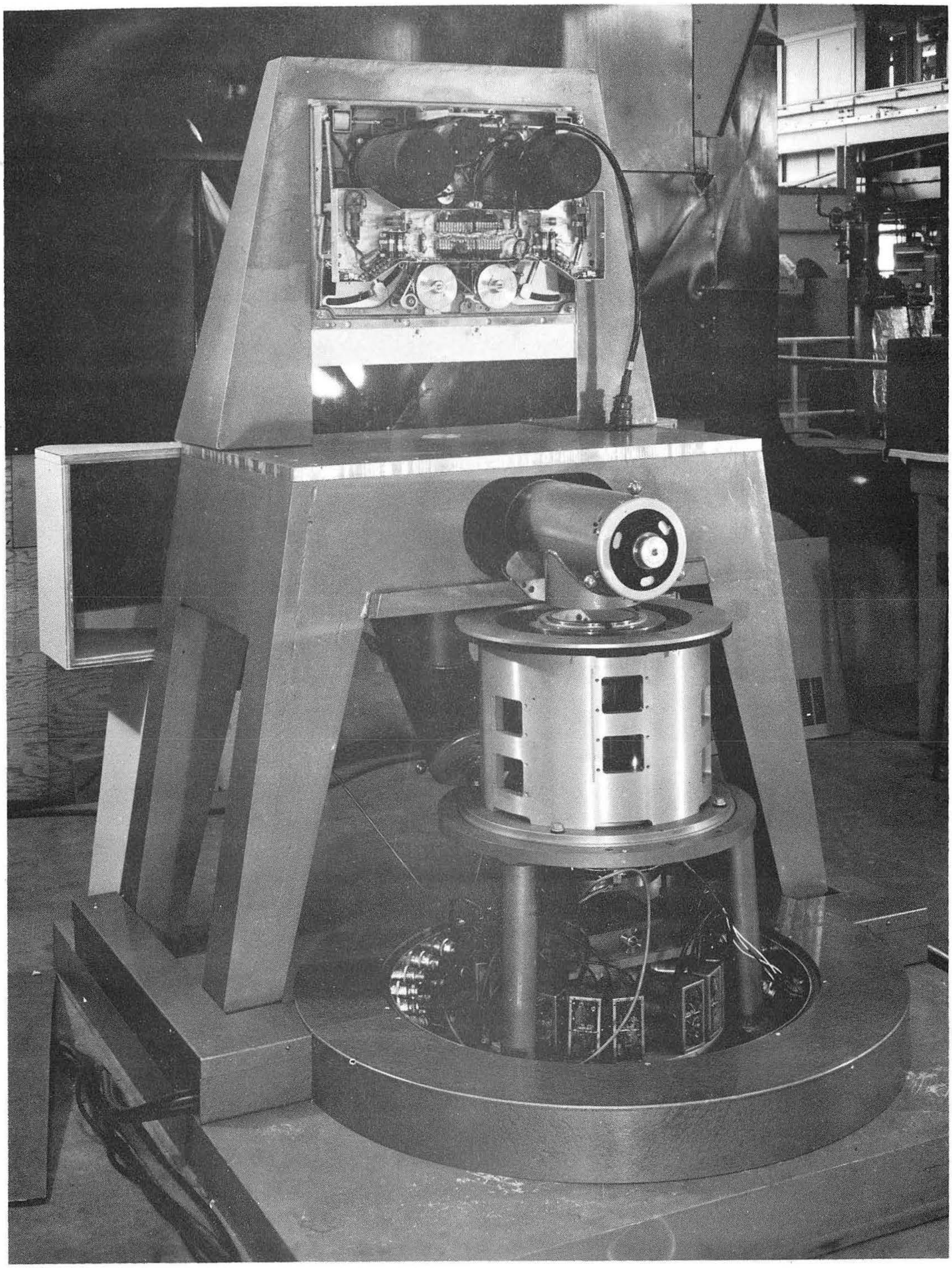
We believe that there are several possible solutions to making the measuring machine itself.

We are not so sure that we can teach the machine to recognize a large enough fraction of the events that we wish to have measured. Or that we can instruct the measuring machine with enough accuracy and versatility. The McCormick reader, and mocked-up spiral scans on the Franckenstein, are just starting to be used to investigate this. We cannot say anything at the present time.

It is possible that machine scanning, and human scanning, will be made easier by displaying the films with closed-circuit television, having delay-line circuits similar to radar moving-target indicators, so that tracks going all the way through the chamber without interaction will not be displayed on the screen. Squeezing down the length of the image, or enlarging any desired region, are obvious possibilities too. We have only started gathering equipment for this preliminary study. We have not tried it yet.

It is not realistic to think that we will be content to ignore or throw away all events that fail to go through our system. We will, in fact, want to examine all of them to be sure that we have not overlooked important new physics. If the failure rate is as low as 2% (very unlikely, considering the complexity of the recognition and instruction problems and programs), then in principle we could re-examine the events that failed, and put them through the Franckenstein system. However, it seems that we could profitably develop a device (simple compared with the things we've been talking about) for the specific purpose of reworking film that has failed to satisfy the criteria we established in the first analysis. A most important characteristic of this specialized device would be attention to simplifying the physicist's task of examining and measuring the film and of allowing him to interrogate the attached computing machine regarding alternative interpretations of the event. We expect that the components of the super-high-speed device, without character recognition, might be adapted to this machine. (That is easy to say, since both devices are still fantasy.) Interrogation programs might not be a trivial development, since by implication we would need working debugged programs for nearly every alternative interpretation.

It is evident that we are still a long way from analyzing all the good high-energy physics that exists in bubble-chamber photos.



ZN-2345

Fig. 5

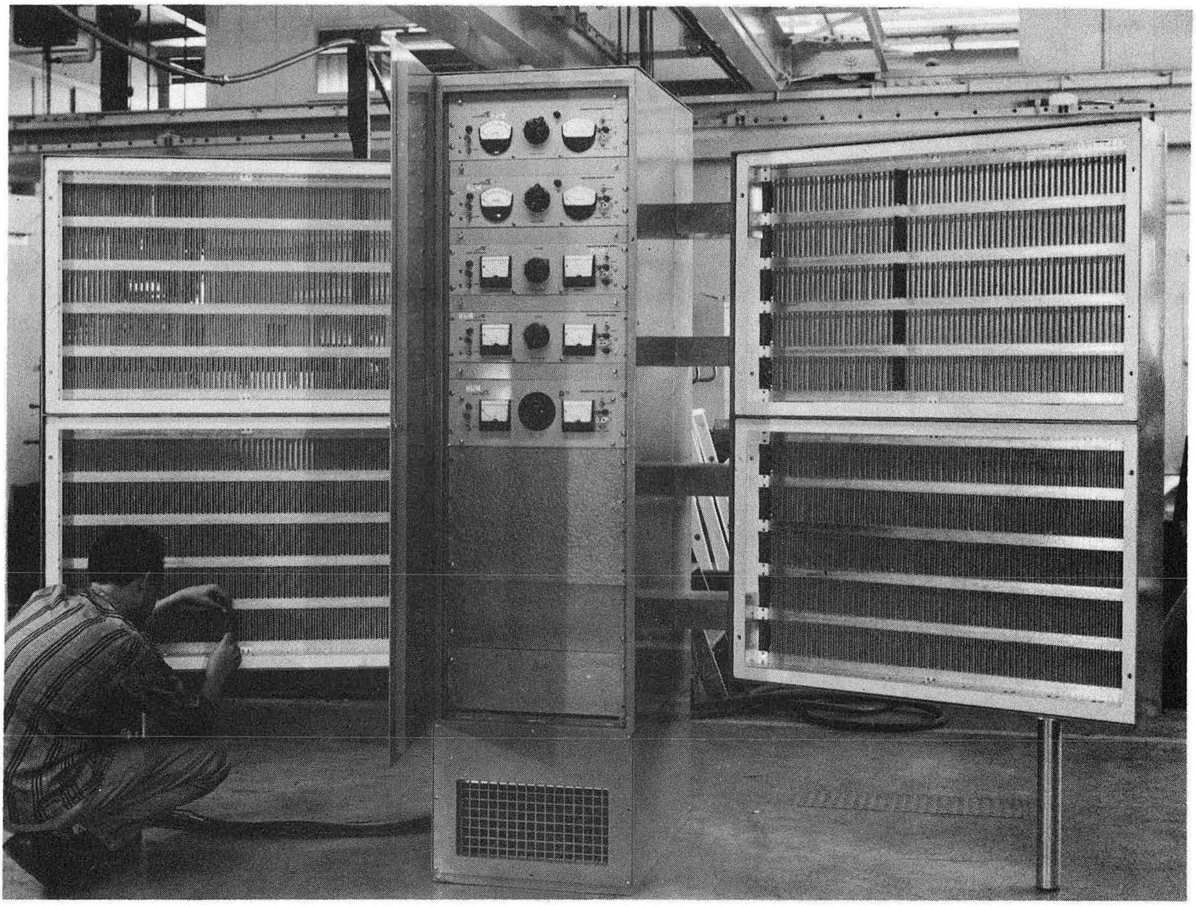


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Fig. 6

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ZN-2341

Fig. 1

3. Measure

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Fig. 2

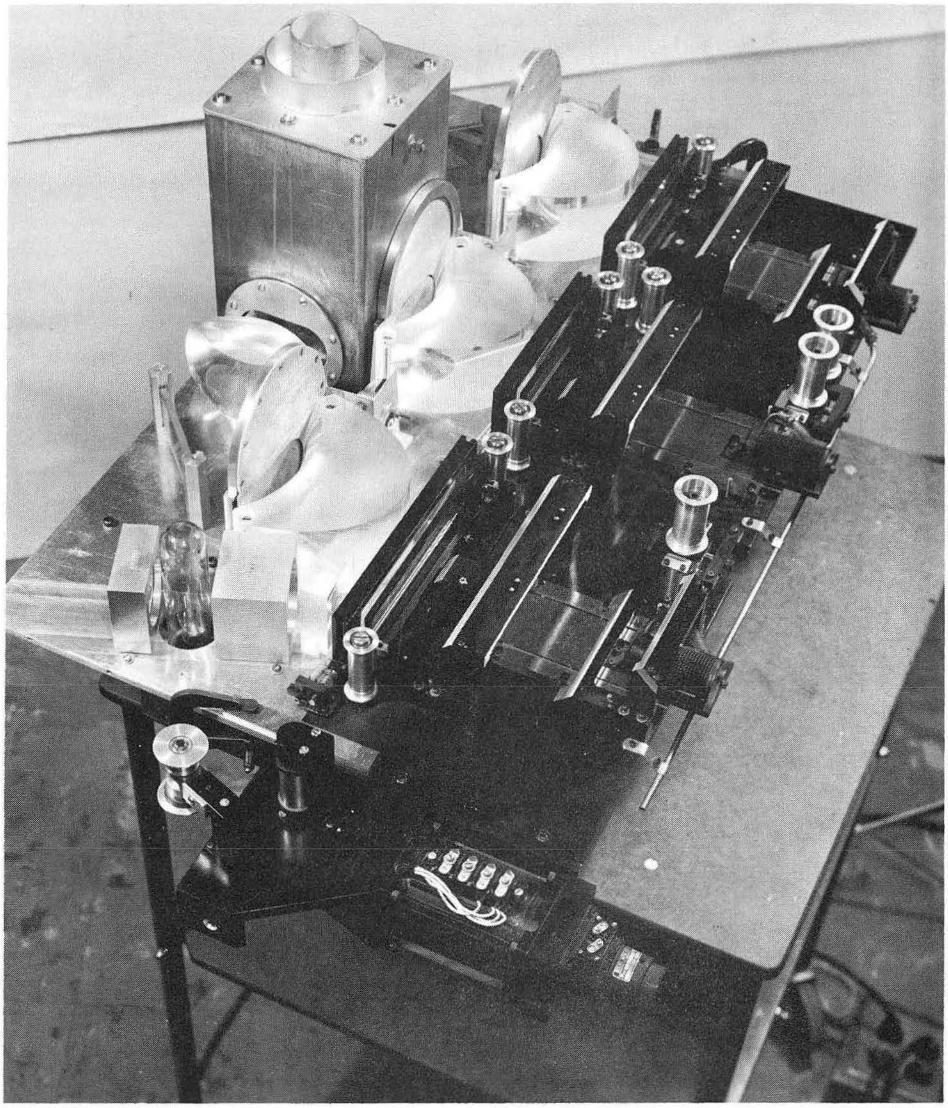

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Fig. 3.

5. Examine

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7. Keep Records

6 min/event

The tabulations of events found in scanning must be correlated, and the records must be kept for reference. The "sketch cards," which now are 8-1/2 × 11 McBee Keysort cards, must be filed, as well as the printouts from the computer. All this is being done now by one extremely good person, plus the physicists as they use the data. But it is a cumulative job which will need to be mechanized soon. We have looked briefly into normal actuarial and business methods. IBM Ramae does not meet all our needs. Perhaps we can use some new library sorting and recall techniques, such as ITEK is developing.

The times for these operations seem fairly well balanced. Three or four scanning machines and one Franckenstein can process 20,000 event per year. Actually, we did 10,000 events from the 15-inch chamber during 4 months last year with four scanners and two Franckensteins. The Franckensteins were not fully scheduled on week ends.

About 2 minutes can be saved in all the bottleneck operations by putting automatic frame selection on scanners and Franckensteins, and by improving the interlocks that force the operator to make all measurements in the correct order. These things are being built. Automatic transfer of the physicist's instructions from the sketch to the Franckenstein and the computer will be done later if it seems necessary.

Experience with the 72-inch film is brief, and may give some surprises. Scanning per picture is certainly slower. To a first approximation, we find that it takes four times as long per picture, since the eye can see only a limited area at a glance. We find that we can stand only the same number of tracks per picture (20 or 30) without confusion or ambiguity. Hence, the scanning time per interaction is about the same as in the smaller chambers.

It would appear that the Franckenstein system can be made to handle 70,000 to 100,000 strange particle events per year, by using three or four measuring machines, 12 to 15 scanning machines, and a staff of about 50 technicians. About five full-time physicists will be needed for the analysis--not including programming.

Recently it has become clear that the non-strange-particle interactions are a very important field of investigation in fundamental nuclear physics. Some excellent theorists feel, in fact, that the study of these interactions is now of greater importance than the strange particles. It seems necessary to measure a very large number of events in order to extrapolate with the necessary statistical accuracy into the nonphysical region that is of major concern to the men working in dispersion theory. And in most cases it seems necessary to measure the events to the same high accuracy required for strange-particle studies. The hydrogen bubble chamber seems to be the most powerful tool at the present time for such investigations, because of the large number of interaction types that can appear, and the angular momentum and accuracy required.

So now, we are faced with the problem of analyzing several million events per year. It is obvious that the Franckenstein system cannot be extended to cope with the job. Even I shudder at the idea of 50 measuring machines and 30 to 50 scanning machines grinding away on the film from a single bubble chamber run.

It does not seem reasonable for physicists or technicians to examine the necessary number of pictures, or to enter any appreciable amount of data for a measuring machine at the necessary rate, or to examine the output of the computing machine in detail for each event. We would need to look at one output per second during a normal working year.

Evidently, if we are going to accomplish this task, we must find a way of using a machine to locate the events of interest--a frightening prospect but I do not see any alternative. We must also measure these events automatically, and record and tabulate only those events which have satisfied our initial criteria. We must, of course, be very careful that the events we discard are randomly distributed--the better our statistical accuracy, the smaller systematic error we can tolerate.

The problem of recognizing events automatically is not trivial. In fact, I don't think it has ever been done, with the possible exception of some pioneer work by P. V. C. Hough at Michigan. The task appears less formidable than some of the jobs being undertaken in translation, deciphering of handwriting, or recognition of patterns in aerial photography. It would certainly be necessary to have a large computer attached directly to the apparatus. It may be necessary to design a special computer. The same computer would direct the measuring machine and carry out the analysis of events after they are measured. The computer programs would be very complex.

The problem of making a measuring machine with the required speed and accuracy is a big one, but Bruce McCormick, an extremely capable man, has been working on it for a long time. (He is probably the first man to tackle this job of ultra-high-speed analysis). His mechanical flying-spot machine--called, of course, the "McCormick Reaper" is shown in Fig. 4 as it looked in mid-January. This is a front view of the console with the film transport, which is a modified Ampex tape drive to present the section of the film on which measurements are to be made. An enlarged image of the film is displayed on the transmission screen at the center of the console. The two wings of the console are now filled with indicator lights and control switches. The stage carrying the lens and light system has been removed for this photograph and the next.

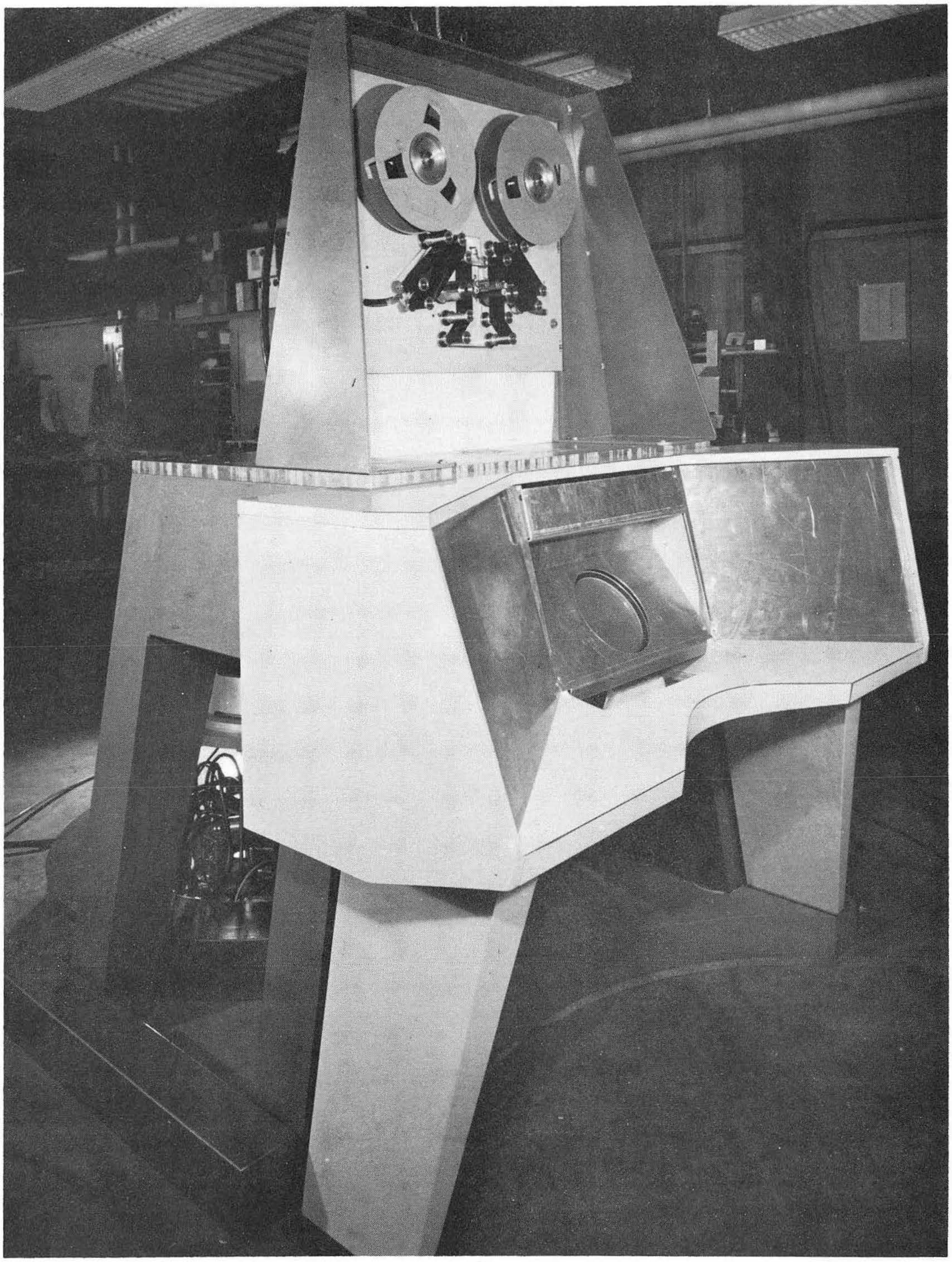

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Fig. 4.

The rear view of the console is shown in Fig. 5. In the foreground is the rotating drum surrounding the slit plate, the Baldwin disk with 2^{16} bits on its outer ring for defining the angular position of the slitted disk, and a system of light pipes carrying the signals from the slits down to the photomultipliers.

The racks to house the transistorized electronics for the controls and some of the computer components are seen in Fig. 6. More than 10% of these racks have been filled since this picture was taken.

(A television flying-spot tube of 50,000-line resolution would be needed to scan an entire picture with the necessary resolution. Trickery may make it possible with less.)

We believe that there are several possible solutions to making the measuring machine itself.

We are not so sure that we can teach the machine to recognize a large enough fraction of the events that we wish to have measured. Or that we can instruct the measuring machine with enough accuracy and versatility. The McCormick reader, and mocked-up spiral scans on the Franckenstein, are just starting to be used to investigate this. We cannot say anything at the present time.

It is possible that machine scanning, and human scanning, will be made easier by displaying the films with closed-circuit television, having delay-line circuits similar to radar moving-target indicators, so that tracks going all the way through the chamber without interaction will not be displayed on the screen. Squeezing down the length of the image, or enlarging any desired region, are obvious possibilities too. We have only started gathering equipment for this preliminary study. We have not tried it yet.

It is not realistic to think that we will be content to ignore or throw away all events that fail to go through our system. We will, in fact, want to examine all of them to be sure that we have not overlooked important new physics. If the failure rate is as low as 2% (very unlikely, considering the complexity of the recognition and instruction problems and programs), then in principle we could re-examine the events that failed, and put them through the Franckenstein system. However, it seems that we could profitably develop a device (simple compared with the things we've been talking about) for the specific purpose of reworking film that has failed to satisfy the criteria we established in the first analysis. A most important characteristic of this specialized device would be attention to simplifying the physicist's task of examining and measuring the film and of allowing him to interrogate the attached computing machine regarding alternative interpretations of the event. We expect that the components of the super-high-speed device, without character recognition, might be adapted to this machine. (That is easy to say, since both devices are still fantasy.) Interrogation programs might not be a trivial development, since by implication we would need working debugged programs for nearly every alternative interpretation.

It is evident that we are still a long way from analyzing all the good high-energy physics that exists in bubble-chamber photos.

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Fig. 5

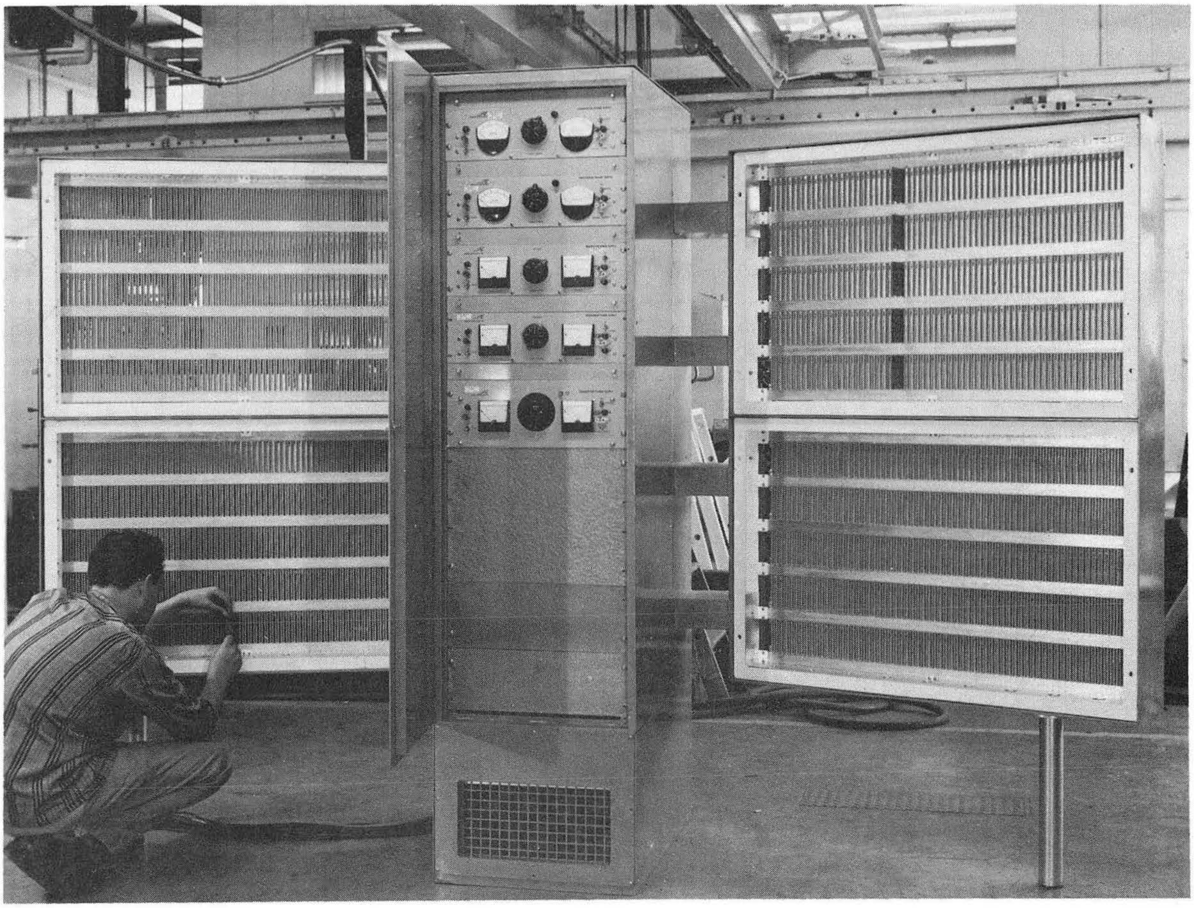

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Fig. 6.