INSTRUMENTATION FOR

HIGH-ENERGY RESEARCH

by George W. Tautfest

Automated measuring of particle events is growing in popularity. Film from visual detectors, such as bubble chambers, can be scanned for events and then measured—all automatically. Detectors that do not require film storage can feed data directly to computers for processing. But the most exciting development in high-energy experiments has been the employment of the computer as an active part of the experimental apparatus.

IN THE HIGH-ENERGY physics laboratory the most remarkable development that has occurred in the last five years has been the introduction of the digital computer as an active part of the experimental apparatus. This development has been due chiefly to the increased number and complexity of detection elements in a typical high-energy experiment and the dramatic decrease in cost of computing equipment. The point here is not the increased use of a computer per se to do numerical calculations in analysis of raw experimental data but its use "on line" as an intrinsic element in a closed control loop to modify the experiment while it is in progress.

As recently as five years ago, it was a standard comment at the conclusion of analysis of experimental data, often long after equipment had been dismantled, that "now we know how we should have done the experiment." Today the experimenter can be supplied with such information in a continuous manner throughout an experiment. He can remain an active element in the control loop making decisions on the basis of information received, or he can allow the system to operate with the computer exercising the control function to the programed end of the experiment.

For the purposes of this article, it is convenient to divide high-energy physics experiments into two categories: those in which an event is more or less permanently stored on a medium such as photographic film and those in which storage time is measured in milliseconds. Experiments of the latter type occur, for obvious reasons, only in the experimental areas of a large accelerator; those of the former type are the life blood of the high-energy physics laboratory at a university.

Many other developments are also occurring in high-energy instrumentation. Detectors such as bubble chambers, multiplate spark chambers and the new wide-gap spark chambers frequently employ photographic film to store information. Attempts are being made to replace human film scanners and measurers with automatic equipment. The most completely automated film scanners digitize the photograph, decide which events are significant, and then measure them.

Except for bubble chambers, however, film storage is not always the best choice. For spark chambers one can digitize the sparks with vidicon tubes or sonic chambers. Another detector, the wire chamber, can feed its output

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to magnetic memory cores or a magnetostrictive wire. For fast time resolution, scintillation counters in large hodoscope arrays are being used. At Brookhaven these detectors are being used on line, and the experimenter is able to alter his experimental arrangement as he proceeds.

Film storage

The classical detection devices using film storage are the hydrogen bubble chamber (figure 1), with the advantages of high spatial resolution and target purity, and the multiplate spark chamber (figure 2), with the advantages of short recovery time, good time resolution and sufficient memory for external triggering. For certain experiments, in which it is important to detect the presence of electromagnetic processes, the heavy-liquid bubble chamber with a working liquid of propane, freon or xenon has been used. Alfred Prodell of Brookhaven[1] has recently demonstrated the use of various hydrogen-neon mixtures as the working liquid in a bubble chamber; the mixtures allow the experimenter to choose the radiation length of the liquid for his experiment while he continues to use hydrogen as the target material.

A new addition to the family of visual detectors is the wide-gap spark chamber, which uses only two electrodes with separations up to 50 cm.[2] When the chamber is filled with a gas such as neon at atmospheric pressure and pulsed with electric fields of the order of 10 kV/cm, particle trajectories are observed as tracks in the gas. The track reproduces the particle trajectory accurately, and precise momentum measurements are possible when the chamber is operated in a magnetic field. The wide-gap or "track" chamber thus appears to combine the desirable properties of the conventional multiëlectrode spark chamber with the high spatial resolution of the bubble chamber and is under intensive development in the USSR and at Harvard, Argonne and the Stanford Linear Accelerator.[3] Figure 3 shows the quality of tracks obtainable in such a chamber.[4]

In all visual devices using film storage, data-processing problems are similar enough to be considered together. The sensitive volume of the chamber is photographed stereoscopically (with two or more photographs). These photographs, stored on film, contain information on particle trajectories in the form of sparks, bubbles or streamers (together with chamber fiducial marks to define the geometry of the photography). In addition one can store coded or uncoded data on the status of devices outside the sensitive volume, such as triggering hodoscope arrays, magnetic fields, separator voltages and chamber operating pressure. The steps of the analysis program are the following (in order):

1. to decide whether the photograph contains an event of the type prejudged to be "interesting" within the aims of the experiment; if not, the next photograph is considered; if yes,

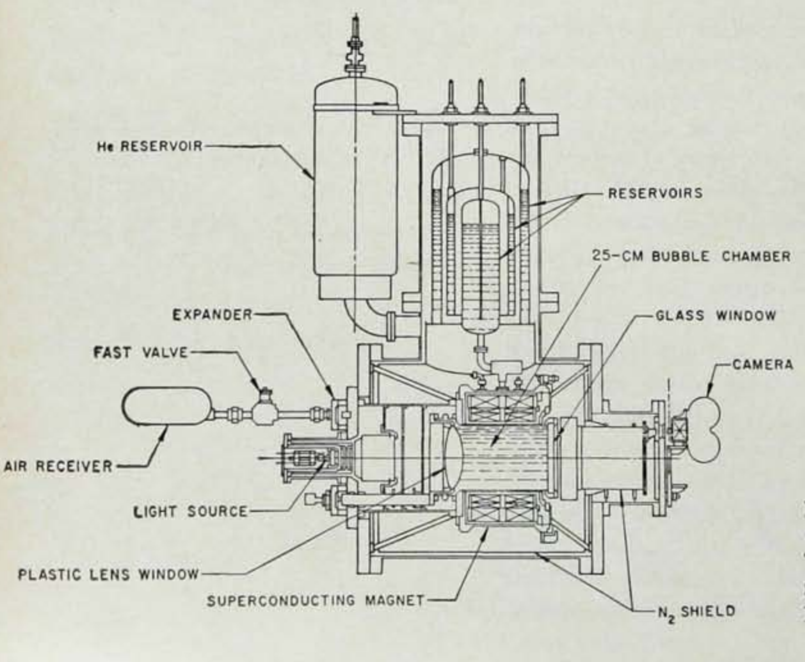
2. to reject all information about track images unrelated to the event and reconstruct in the "real space" of the detection device the particle trajectories defining the event, by

3. application of the known conservation laws to determine the physics of the event.

Human decision making

The old system of film analysis, only now beginning to be replaced, was developed first at Berkeley and later at CERN and Brookhaven. It is a sequential one, with human judgment exercising control directly at each step. Each frame is scanned at a projection table by a human operator, using two or more stereoscopic views to locate interesting events. The location of the event and information about the tracks comprising the event (such as bubble or spark density, decay or interaction along a track) are noted on a sketch card or scan sheet. Next, with the scan information, the stereoscopic views are positioned on a mechanical stage and chamber fiducials and coöordinates of points along the tracks are measured to a precision of several microns on the film (20–50 microns in real space).

The output from the measuring machine is then processed with a computer program designed to make all the necessary corrections for the vary-



BUBBLE CHAMBER has a superconducting magnet to provide a 44 000-kG field. This 25-cm helium chamber is being used for high-energy experiments at Argonne National Laboratory. —FIG. 1

ing optical media that light rays have traversed from the bubble or spark to the image plane of the optical system and reconstruct particle trajectories in real space with estimates of errors. The program assigns masses to particles, corrects for magnetic-field inhomogeneities and energy loss in the chamber medium or electrodes, and gives an estimate of the self-consistency of the measurements. Any operator error in the scanning or measuring process may result in a reconstruction failure; then the event is resubmitted. A second program tests the geometrically reconstructed event against various hypotheses concerning the observed reaction.

At this point it is customary for a physicist to examine the computer output, satisfy himself that the event has been adequately measured and that uncertainties of reconstruction are within reasonable limits and finally to accept a hypothesis for the reaction. When a large enough sample of a given reaction has been accumulated, data are processed by other programs that calculate Dalitz plots and histograms of physical properties of interest in the reaction.

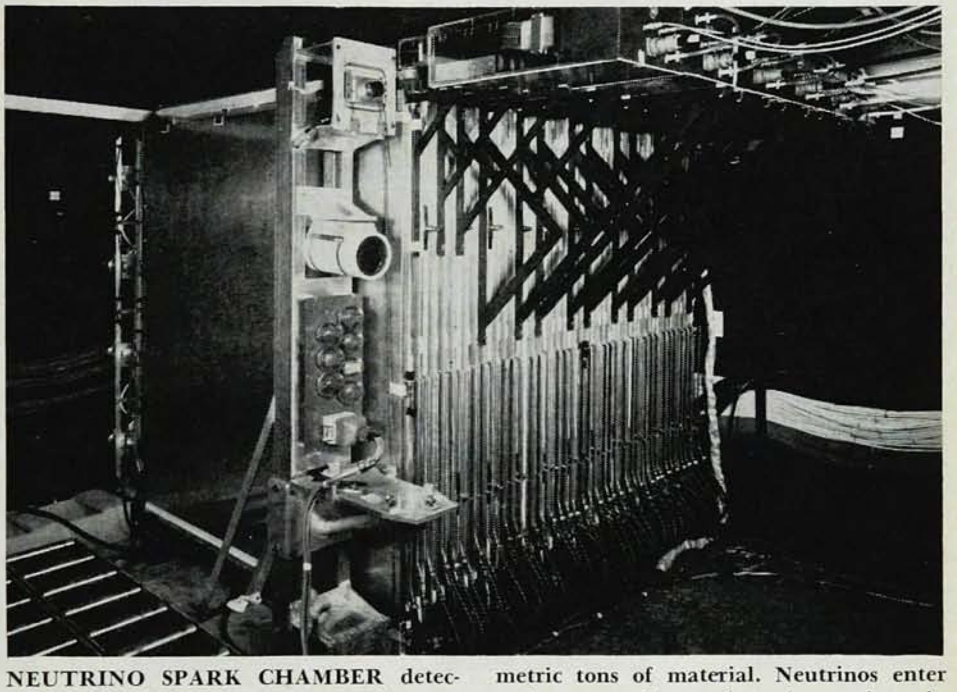
Computer-assisted decisions

The "new system" of film analysis attempts to replace the human operator with automatic equipment and, where the operator must be retained, to supply immediate feedback of the results of an operation for control. The effect is not only to increase the system's speed but also to eliminate errors that might have drastic effects on the throughput rate.

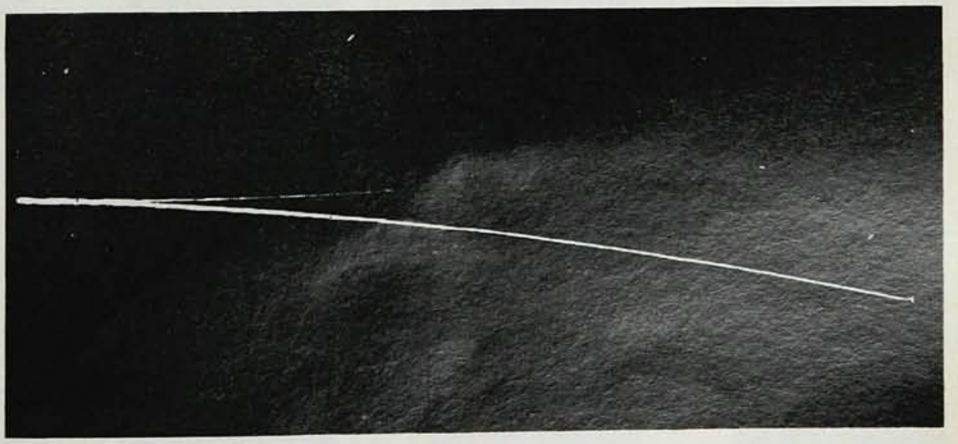
Many laboratories have taken a first step toward automatic film analysis, that of placing scanning and measuring machines on line with a computer. In the system at Purdue University,[5] information from the scanning tables, including ionization measurements, is fed directly into a computer file by teletype communications. When the operator at a measuring machine indicates he is ready to begin measuring, the computer indicates the roll number to be placed on the machine and advances the roll to the correct frame. The computer program leads the operator through the measurement step by step, changing views for him and checking results at each step.

At the end of the measurement, the event is immediately reconstructed and errors are examined. If uncertainties are beyond limits, the program requests a remeasurement; if not, the film is advanced to the next frame on the scan file, and the library event file is updated. The Purdue experience, confirmed by other laboratories, is an immediate gain by a factor of two to three in throughput rate compared with the same machines working off line.

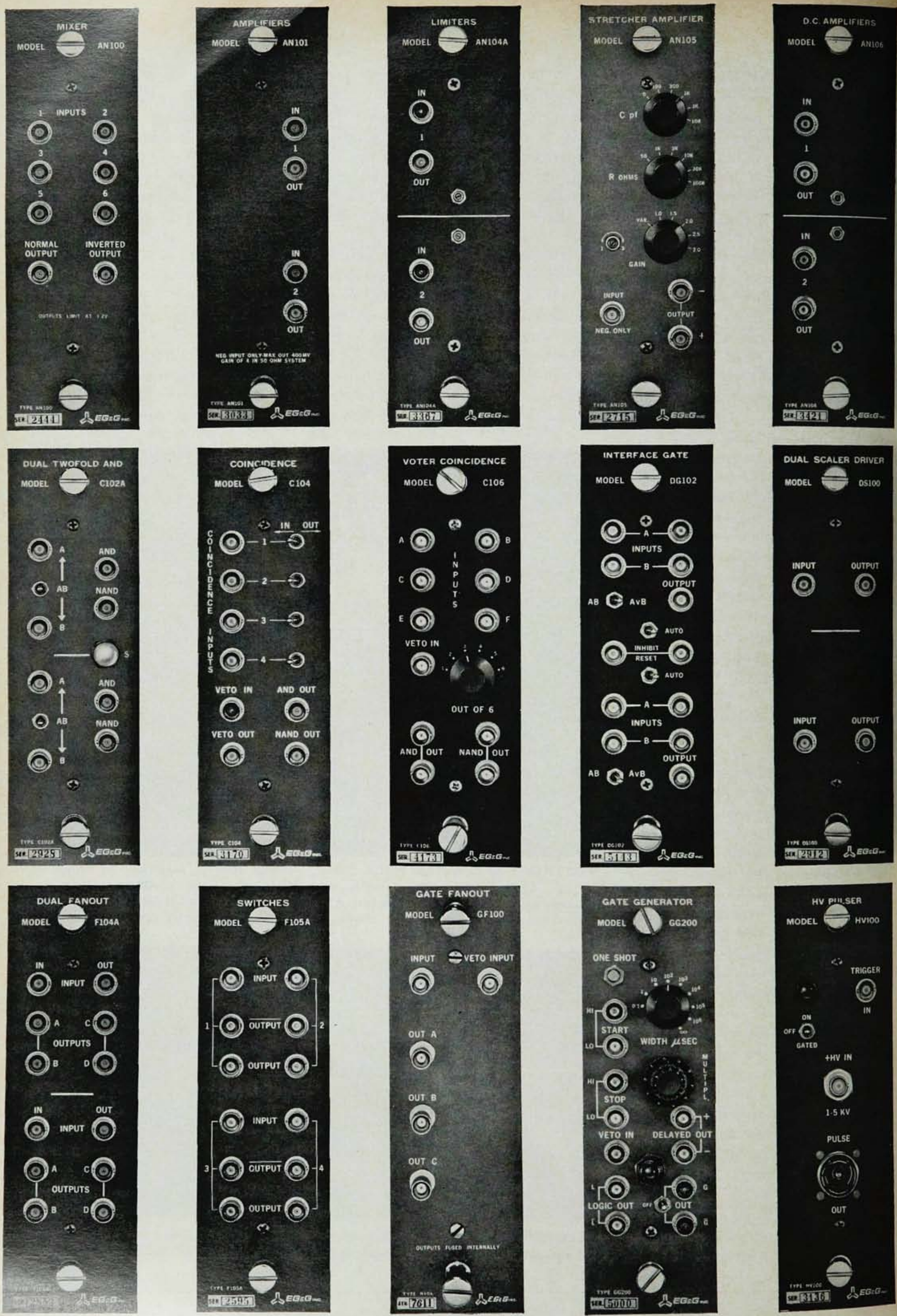
To date the most successful systems for automatic measurement of bubble-chamber film still retain some human elements. The first such system to become operational is the Scanning Measuring Projector (SMP), an invention of Luis Alvarez at Berkeley. In this system the operator is required only to position a measuring head so that the track lies within an aperture about 0.5 cm^2 in area. As rapidly as the operator moves the head along the track, points are automatically digitized and fed directly into the core of the computer. A filter program rejects digitizations not belonging to the track and generates smoothed points corresponding to the precision coördinates obtained from a conventional measuring machine. If the array of smoothed points satisfies certain con-



NEUTRINO SPARK CHAMBER detector at Argonne. Six 30-cm units are stacked together to form a detector with a 600-liter volume, containing about 14 metric tons of material. Neutrinos enter and occasonally produce interactions in the detector material. Cameras can be seen at left end of device. —FIG. 2



ELECTRON-POSITRON PAIR produced in top plate of a 40-cm wide-gap spark chamber placed in a magnetic field. Chamber operated in the spark mode.—FIG. 3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MODEL AN106
IN
OUT
DUAL TWOFOLD AND
MODEL C102A
AND
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COINCIDENCE
MODEL C104
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MODEL C106
INPUTS
VETO IN
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AND OUT
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INTERFACE GATE
MODEL DG102
INPUTS
OUTPUT
AB AvB
AUTO
INHIBIT RESET
DUAL SCALER DRIVER
MODEL DS100
INPUT
OUTPUT
DUAL FANOUT
MODEL F104A
IN
OUT
INPUT
OUTPUTS
SWITCHES
MODEL F105A
INPUT
OUTPUT
GATE FANOUT
MODEL GF100
INPUT
VETO INPUT
OUT A
OUT B
OUT C
OUTPUTS FUSED INTERNALLY
GATE GENERATOR
MODEL GG200
ONE SHOT
START
WIDTH μSEC
MULTIPL.
STOP
VETO IN
DELAYED OUT
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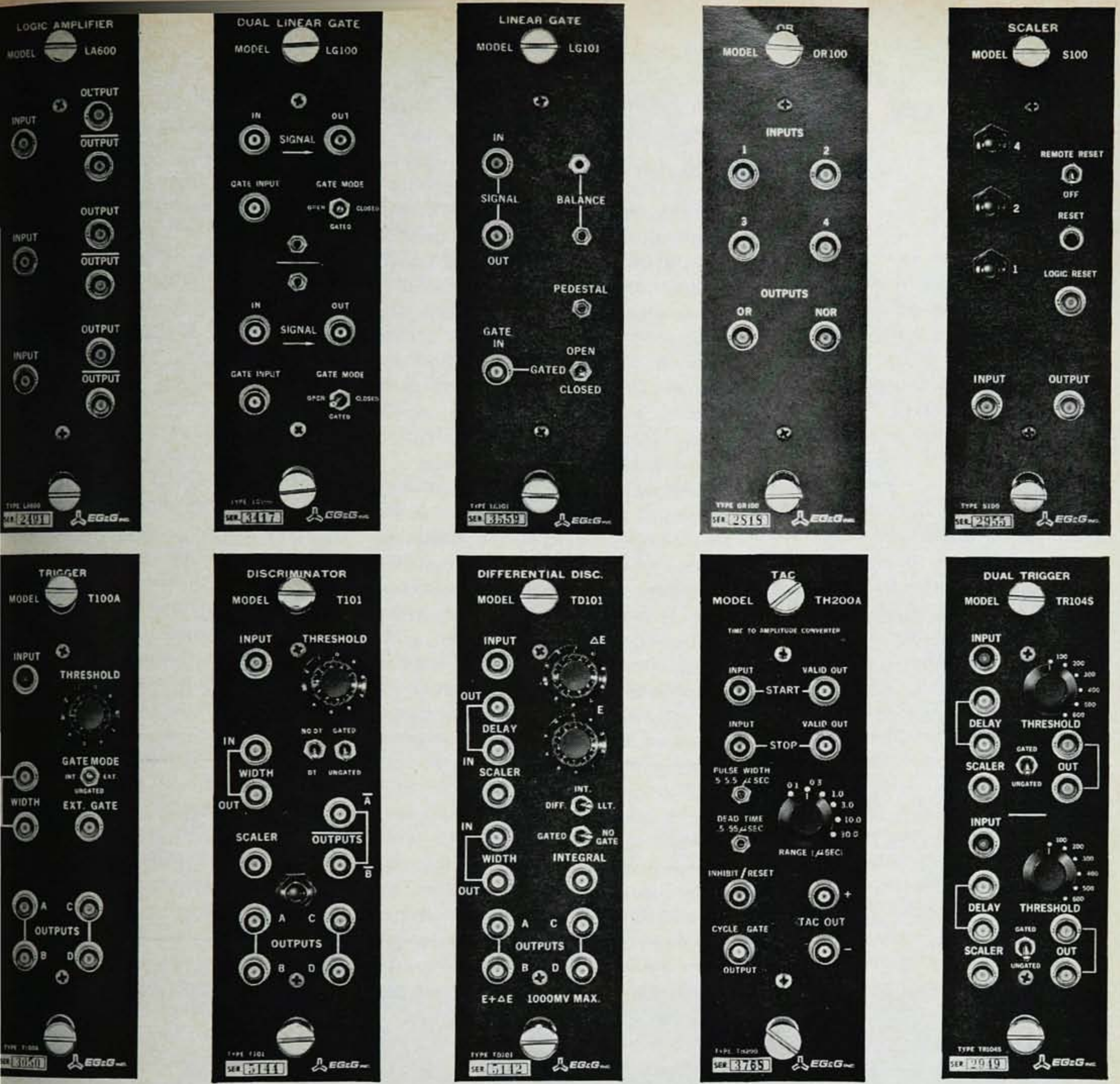

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tinuity criteria, the operator is told to measure the track in another view; if not, the type of difficulty encountered is transmitted with a request for a remeasurement.

Quality of measurements is comparable with that of the conventional machine, with about twice the speed for the same cost. A computer of the IBM 7044 class can handle the simultaneous output of 5–20 SMP tables, depending on the amount of auxiliary computing desired. SMP systems exist at Lawrence Radiation Laboratory, the University of Illinois, Purdue University, Carnegie Tech, the University of California at Los Angeles and the University of Heidelberg. The University of Hawaii has an SMP system for analysis of spark-chamber photographs.

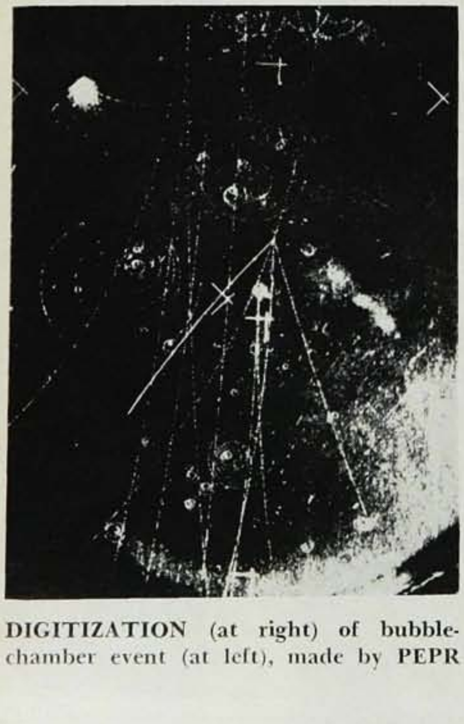
Another system, the Spiral Reader, also developed at Berkeley, reduces the operator's function to positioning the photograph so that the vertex of the event is centered in the measuring head. The entire photograph is then digitized automatically by a mechanically driven spiral sweep. The output is fed into a filter program that rejects data from tracks not originating from the vertex and produces smoothed points along the tracks that define the event.

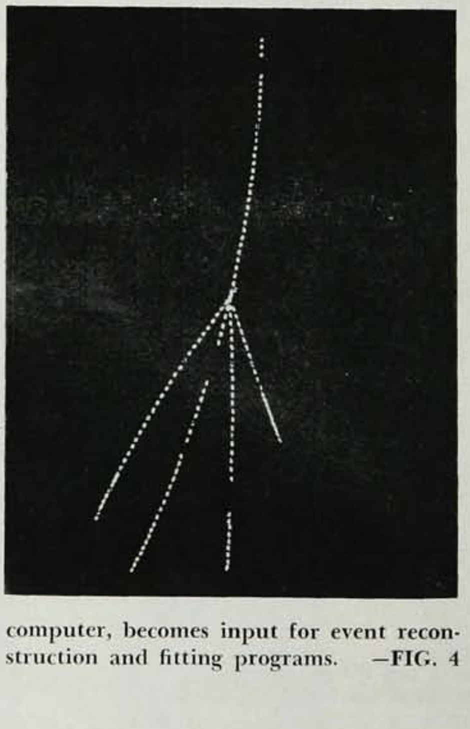
Automatic film analysis

Systems that provide for completely automatic analysis of spark-chamber and bubble-chamber photographs digitize the entire photograph by sweeping a fine spot of light over the film in a raster pattern similar to a television scan. A photomultiplier behind the film detects the presence of a spark or bubble, and the coördinates of the spot position are recorded at the time of the "hit."

The various systems that have been developed differ chiefly in the manner in which the flying spot is generated. SPASS (MIT), LUCIOLE (CERN), CHLOE (Argonne), SASS (LRL) and ARIANE (Orsay) generate the flying spot with a precision cathode-ray tube. The Hough-Powell device (HPD),[6] used in Brookhaven and CERN systems and in the FSD system at Berkeley, employs a system of fixed and rotating slits combined with the movement of the film to achieve the systematic scan.

The scan output is stored in a memory until the scan for the frame in question is completed. The computer program then initiates the scan of the next frame and processes the stored information from the previous frame. Fiducials are recognized, sparks are organized into tracks and background sparks are rejected.





DIGITIZATION (at right) of bubble-chamber event (at left), made by PEPR computer, becomes input for event reconstruction and fitting programs. —FIG. 4

Since the confusable background is considerably higher in bubble-chamber photographs, the analysis is aided by a predigitizing process known as "road making." The roads, made on the scanning table, are rough predigitizations of the tracks comprising the event. They are used by the computer to select, from the totality of coördinates supplied by the flying-spot digitizer, those to be used in reconstructing the event. The coördinates thus selected are passed through a filter program that rejects digitizations arising from crossing tracks, delta rays, scratches, dust, etc., and produces smoothed points along the tracks.

A more tightly controlled digitizer, which consequently requires a smaller memory, is provided in the PEPR system under development at MIT and Yale.[7] In this system a fixed-program special-purpose computer controls position and azimuth of a line segment generated by a cathode-ray tube and quadrupole system. A photomultiplier behind the film senses the match between the generated line segment and the line segment of a track. Information from the film is used to guide the scan, and track segments that do not link to form an event are quickly rejected. At present some predigitizing is required for bubble analysis, as in the raster-scan systems. Figure 4 shows a PEPR scan of a bubble-chamber photo.

Once the sparks have been organized into tracks or the smoothed output from a filter program has been obtained, the data proceeds through the reconstruction and kinematic fitting programs as before. Since the entire program can be under computer control with continuous feedback, difficulties can be handled as they are encountered. As a last resort the system can request human intervention!

Filmless storage

Although film storage allows the university data-analysis laboratory direct access to the accelerator experimental floor despite separations of thousands of miles, film may offer no advantage and be at best an expensive convenience for experimental groups physically located a few hundred feet from the accelerator. It is not surprising, therefore, that considerable effort has been expended during the past three years on filmless visual detectors.[8] For the bubble chamber, with its special advantage of high spatial resolution, there appears to be no immediate substitute for film. The best vidicon tubes that manufacturers are willing to discuss offer resolutions still a factor of 5–10 lower than acceptable.

For spark chambers, on the other hand, the vidicon technique is capable of direct digitization of spark coördinates with the precision and short dead time required.[9] Chamber scanning is usually parallel to the gaps with both stereo views of the chamber arranged in a mirror system so that they can be viewed with one camera. Physics results are already available from this technique.[10]

A second method of direct digitization of sparks uses the shock wave propagated in the gas when the spark is formed. The acoustic or sonic chamber uses microphone circuitry in each gap to determine the spark coördinates. The presence of more than the minimum number of microphones in each gap, coupled with sophisticated electronics, allows resolution and location of multiple sparks.

Direct readout of the data from the vidicon or acoustic network into a computer provides constant monitoring of the detection system, and the events accumulated during the beam pulse can be completely analyzed between pulses.

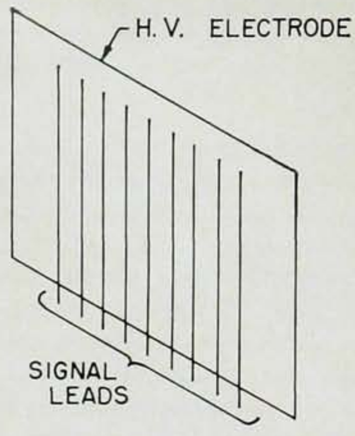
Finding the sparks

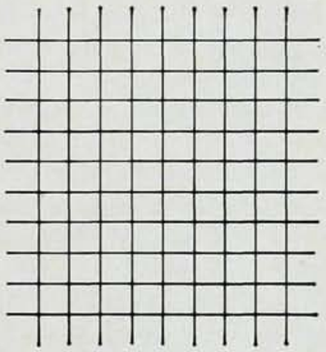
A different type of direct-readout chamber is obtained by replacing the plane electrodes in a multiplate spark chamber with a grid of parallel wires (figure 5). When the high-voltage electrodes are pulsed, the spark resulting from passage of an ionizing-particle through the gas produces a current in the struck wires. Since a given plane yields position information in only one dimension, a second plane with wires running at right angles to the first supplies the other coöordinate. To resolve ambiguities resulting from multiple sparks a third plane oriented at 45 deg is added. Typical wire spacing is about 1 mm, yielding spatial resolution of the order of 0.3 mm.

Since the sparks need not produce enough light for visual recording, the energy of the spark can be kept low; this low energy results in a fast recovery (200 microsec) and a short resolving time (0.5 microsec). A useful property of the wire chamber is the low mass introduced into the beam compared with the conventional multiplate spark chamber or scintillation-counter hodoscope. Joachim Fischer[11] has described a technique of making etched circuit-board planes up to a square foot in area with a mass equivalent of 1.5 meters of air for particles striking the plane normally.

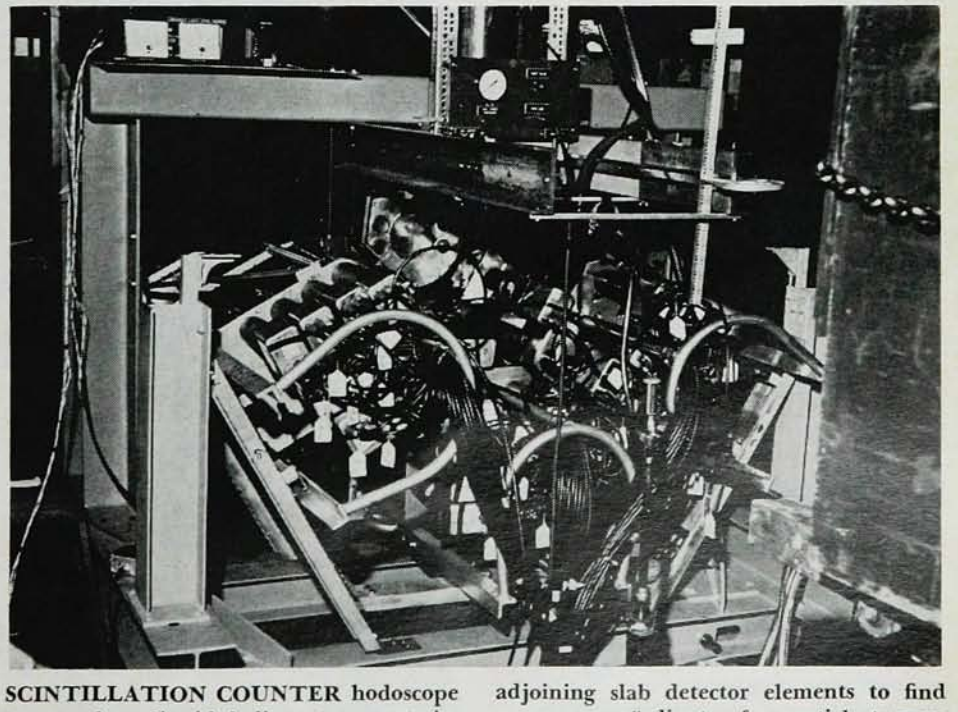
The most widely used technique at the moment employs magnetic memory cores to record which wires were struck by sparks. After the high-voltage pulse the cores are scanned, and addresses of the sparks are generated and stored in a buffer. The read time is comparable with the recovery time of the planes themselves, and several hundred events can be accumulated in the buffer during the beam pulse. Between accelerator pulses data are transferred to a computer, and events are analyzed.

In another system the spark location is determined by magnetostriction. The magnetic field associated with the spark produces an elastic deformation of the wire, which propogates as a longitudinal wave at the velocity





WIRE SPARK CHAMBERS. Two kinds are shown schematically. Single-coördinate chamber (top) is made of a wire-grid electrode and a high-voltage sheet. Two-coördinate chamber (bottom) uses vertical wires as one electrode and horizontal wires as another electrode. —FIG. 5



SCINTILLATION COUNTER hodoscope surrounds a liquid helium target at Argonne. A hodoscope array uses long, thin, adjoining slab detector elements to find one space coördinate of a particle traversing its plane surface. —FIG. 6

of sound in the wire. The wires of the chamber can be made of ferromagnetic materials; then the signal is detected by a pickup coil in close contact with the magnetostrictive wire.[12] The arrival time of the magnetostrictive pulse yields one coördinate; the second is that of the wire itself.

An alternative method[13] employs a magnetostrictive wire coupled magnetically to the ends of the nonmagnetic wire grid. Both ends of the grid wires feed into an acoustic delay line, yielding one coördinate in terms of delay and the second as a function of pulse height.

For applications requiring extremely fast time resolution, the scintillation counter is still the first choice, and its use by S. J. Lindenbaum and Luke Yuan[14] in large hodoscope arrays was one of the first applications of large-scale on-line data analysis. They are now using a hodoscope (figure 6) with elements that yield a spatial resolution of 3 mm; that is, within a factor of 5–10 of the wire chamber, with the advantage of a much higher counter rate.

On-line experimental control

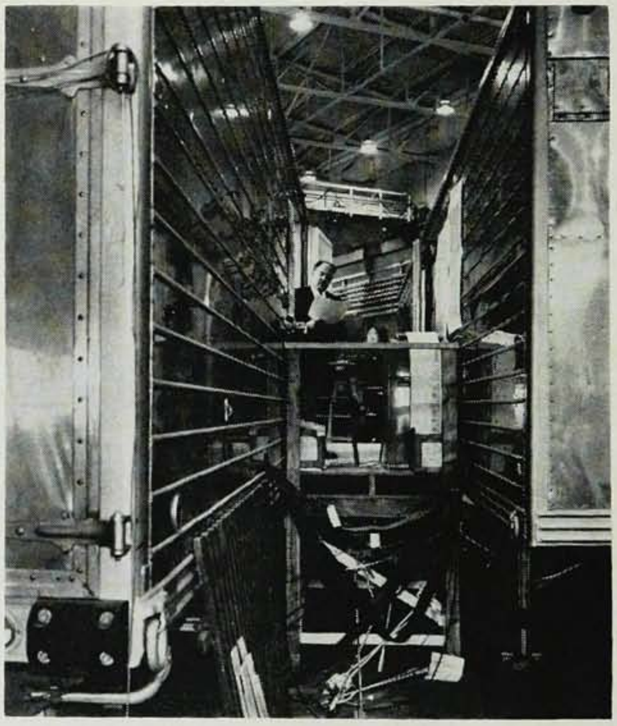
Organization of these highly developed detection techniques into a system capable of reliably processing the enormous amount of data potentially available is a major undertaking. It frequently involves a long and painstaking setup using the skills and experience of many physicists and requiring much advanced programing for computer use.

As an example we consider a current Brookhaven experiment[15] to measure inelastic proton-proton scattering over a wide range of angles and incident energies. Using the experience acquired over the past five years by the Lindenbaum-Yuan group, Brookhaven has developed a physics department on-line data facility for its user groups. This facility, which is built around a PDP-6 computer, includes a time-sharing monitor system, several high-speed tape transports, a 300-line/min printer, and a display oscilloscope. The PDP-6 is mounted on two vans that can be moved around the floor of the Alternating Gradient Synchrotron in close proximity to the experiment (figure 7). Similar facilities are under development at the Cambridge Electron Accelerator[16] and the University of Chicago.[17]

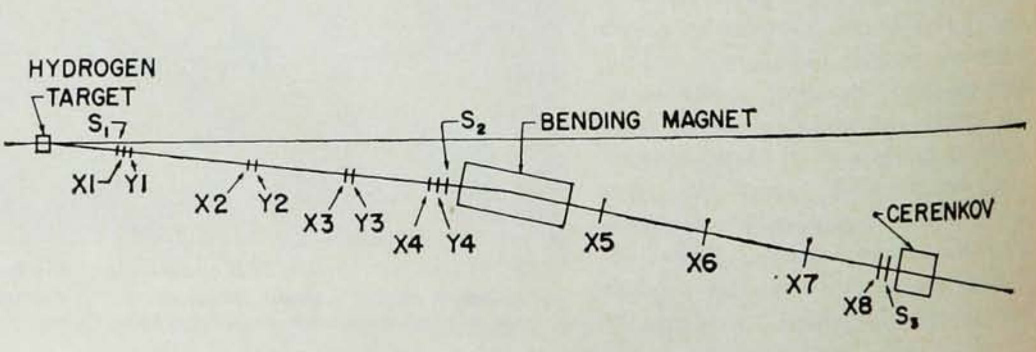
The Brookhaven experiment employs spark-discharge planes[11] arranged as shown in figure 8. Figure 9 is a block diagram of the data-handling system.

The wire planes are pulsed by a suitable coincidence between scintillation counters S1, S2, S3 and the threshold gas Cerenkov counter, which rejects pions. The scattering angle is determined by the four X (horizontal) wire planes and the four Y (vertical) planes. The second set of four X planes, following the bending magnet, determines the momentum of the particle. The distance from X1 to X8 is about 30 meters.

The same triggering logic that pulses the chambers initiates the readout system, which reads the cores and assembles and stores the spark addresses in the 4096-word buffer. The event rate is limited by recovery time of the discharge planes and, in conservative operation, to ensure long life and trouble-free operation of the chambers, the rate has been limited to about 150 events per AGS pulse (300 millisec). In the 2 sec between beam pulses, data



ON-LINE DATA facility at Brookhaven is built around a PDP-6 computer housed in two trailers that can be moved around AGS floor. S. J. Lindenbaum stands by one of five teletypes used in time sharing. —FIG. 7



PARTICLE spectrometer shown schematically uses spark-discharge planes and an analyzing magnet for accurate space and momentum measurements. —FIG. 8

is transferred to the computer, where it is processed event by event in the following steps:

1. The spark addresses belonging to a particular event are decoded in terms of the coördinates of each plane.

2. The events in which at least three out of four planes in a segment have a good cluster of sparks are fitted with a straight line. If the deviation of any one point from the fit is more than the allowed number of wire spacings, the event is rejected.

3. The particle trajectory before and after the bending magnet is determined in the laboratory coördinate system, and the polar and azimuthal angles of scattering are calculated.

4. Particle momentum is determined and corrected for inhomogeneities in the analyzing magnet.

5. Histograms of accepted events are calculated and updated, and correlations of experimental parameters in preselected ranges are calculated.

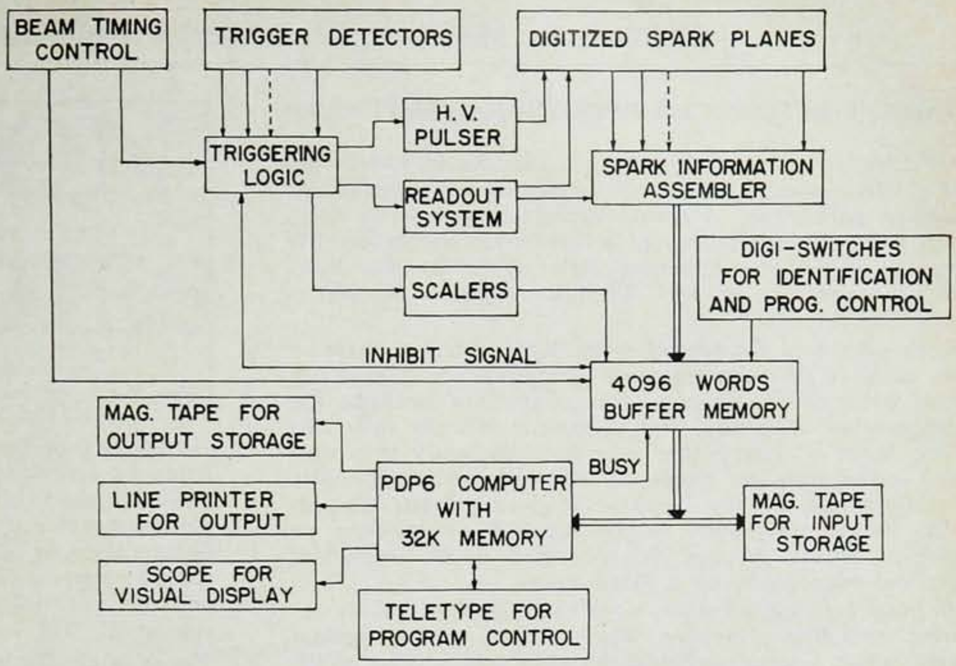
6. The file tape of events is updated for a more sophisticated analysis to be performed off line.

7. On demand, a current summary of event parameters is printed out or displayed on an oscillograph.

Thus the experimenter can at all times be assured that his equipment is functioning properly and can alter the direction of the experiment on the basis of results obtained to any moment. It would be but a small step further to use the computer in a completely closed loop to control the operating conditions of the accelerator and beam-transport system so that optimal beam conditions would be maintained during data acquisition. Beam-energy changes and choice of secondary particles could be made on demand or as a programed result of collecting sufficient statistics.

An important conclusion to be drawn from this example is that design and construction of such a facility calls for organization of diverse skills on a magnitude we have formerly associated only with the design and construction of the accelerator itself.

It would be a mistake to conclude from this discussion that all experiments are necessarily appropriate for on-line-computer operation. The type of programed research now coming into existence can be welcomed by all physicists for the freedom it provides to concentrate on analysis and interpretation of the experiment. With automatic handling of most data the experimenter is liberated from routine housekeeping that soon loses its instructive value even for the beginning graduate student. Instead he can pursue one-of-a-kind events: rejects and no-fits in which surely important and exciting phenomena remain to be discovered. □



TYPICAL on-line data-handling system. Signals from spark-discharge planes and counters in detection system are transmitted through the fast gates. —FIG. 9

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