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RECENT DEVELOPMENT IN SPARK CHAMBERS

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Feb. 28, 1966

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Abstract

The parallel developments of a variety of spark-chamber schemes have produced many workable systems with success in experimental applications. Major efforts have developed several methods for direct electrical readout of spark-chamber data. These include the use of magnetic cores for direct digitizing of information from wire spark chambers, as well as the use of Vidicon cameras to observe sparks, and of current division and acoustic transit time in analogue devices to measure spark position. For such systems the on-line use of computers, and (or) the construction of significant electrical interfacing circuitry, are important considerations in efforts to maximize the event rate. Conventional spark-chamber systems using film to record data have benefited from the continued development of automatic off-line scanning and measuring systems. There are also many experiments that will use the unique capabilities of wide-gap spark and streamer chambers.

I. Introduction

The continued development of spark-chamber systems in great variety reflects primarily the many different experimental requirements of particle physics. For this reason there is no one best system, and the richness in the choice of detail contributes vitally to the challenge to those designing spark-chamber experiments. In many cases a large prior investment in a particular method of data handling influences strongly the selected program of a given research group. At present it appears that as much effort is going into problems of data analysis as into the development of spark-chamber hardware. This is not surprising, because it has become commonplace for a research group to spend as long a period in data analysis (or in preparation of analysis equipment) as in preparation of other equipment and in execution of the experimental run.

II. Spark-Mode Wide-Gap Chambers

Since the initial development of the wide-gap spark chamber by the Erevan group,¹ this type has been studied extensively.² As compared with a narrow-gap chamber of the same volume, the wide-gap chamber puts less scattering material in the beam, provides more measurement

accuracy, and can accommodate a more flexible optical system. Disadvantages of the wide-gap chamber include the need for high voltage (≈ 10 kV/cm), the inability to handle tracks at greater than 40 deg to the electric field, and a rather long clearing time, typically an order of magnitude greater than for a chamber with 1-cm gaps.

Measurement Precision

Use of two adjacent gaps with opposite electric fields (Fig. 1) allows the outer electrodes to be near ground potential and, in addition, affords a means of estimating the coherent displacement produced by electron drift during the rising pulse. Most of this displacement can be eliminated with an adjustable clearing field of order 100 V/cm.^{3,4} However, some curvature remains, introduced by drift gradient associated with the transit-time delays in spark development.⁵

To avoid spurious curvature, the electric field must be uniform in space.⁵ This is ordinarily accomplished with a resistance or capacitance divider along the sides of the chamber to preserve flat equipotential surfaces throughout. Tracking accuracy within 1 mrad in angle and 0.2 mm in position has been obtained in 4-in. chambers.³ With a 13.3-kG magnetic field, a measurement precision corresponding to a 1.4% error at 1 BeV/c was obtained in a 40-cm chamber.⁵

Intensity

The very sensitive dependence of spark brightness on track angle to the electric field has been systematically investigated by the Argonne National Laboratory group,³ who find, using a Ne-He mixture, an exponential dependence of brightness on angle. From 0 to 40 deg the brightness falls a factor of about ten.

Use of Alcohol or Other Organic Vapors

With a few percent alcohol in the chamber gas, improvement in track quality by a factor of two has been obtained. This gives a corresponding reduction in local incoherent track displacement, at the expense, however, of track brightness, which is reduced three to four orders of magnitude for a 4% alcohol mixture.³

*This work was done under the auspices of the U. S. Atomic Energy Commission.

Sensitive Time

Disadvantages of the naturally long sensitive time ($\geq 5 \mu s$) of wide-gap chambers can be partially overcome in several ways. First, because of the decoupling provided by the long sparks, more simultaneous tracks can be detected in wide-gap chambers than in narrow-gap chambers. Second, some methods depend upon the fact that, for "old" tracks, the electrons have time to diffuse away from the track. For these there is less chance for individual avalanches to coalesce into a spark, and the brightness is therefore less;⁶ such tracks also appear granular.⁵ This effect can be further enhanced in two ways, by delaying deliberately the pulse to the chamber⁷ and by reducing the pulse voltage below threshold for developing "old" tracks.⁶ Third, electro-negative gases can be used, but the track quality suffers considerably. Fourth, a clearing field produces opposite coherent displacements in a two-gap (alternate polarity) chamber, especially if there is a magnetic field at right angles to the electric field. This effect also helps to identify old tracks. Hence it appears that wide-gap chambers can be used with resolutions of order $1 \mu s$ if extra tracks (old, but identifiable) or some deterioration of track quality is permissible.

Desensitization

It has been known for some time that an insulating layer can be used to desensitize regions of a spark chamber, and wide-gap chambers can be desensitized similarly by means of Styrofoam discs on the electrodes.³ Another method using a Mylar bag full of helium proved very effective for pulse voltages below 10 kV/cm .⁸ The outer parts of the chamber retained full sensitivity, even with central beam fluxes up to 2.4×10^{11} protons per second. Advantages of this latter method are that the distortion of the electric field is probably negligible, an incident beam profile can be observed with suitable adjustment of the electric-field intensity, and the gas in the bag can be used as a target in "pencil beam" types of experiments.

V's in the Chamber

One of the most impressive and interesting recent developments has been the observation of V's in wide-gap spark chambers by both a Soviet⁹ and a Princeton¹⁰ group. (See Fig. 2.) Although some loss of intensity occurs, sharp tracks are observed, with a diffuse current completing the spark circuit to the electrode not crossed by the charged particles.

III. Streamer-Mode Wide-Gap Chambers

The nearest approach to a useful isotropic chamber is the wide-gap chamber operated in the streamer mode. With the application of a very intense but short pulse, spark development is arrested so that only short streamers along the path of the particle are produced. These luminous centers (~ 3 to $4/\text{cm}$) are, with best current technique, ~ 1 to 2 mm across and $\sim 3 \text{ mm}$ in

length (in the direction of the electric field^{11, 13}). Advantages of operation in the streamer mode are as follows:

- 1) The sensitivity is nearly isotropic.
- 2) Because of the limited development of the discharge, the centers of luminosity tend to be decoupled; hence:
 - (a) A large number of simultaneous tracks, more than for other types of chambers, can be detected.
 - (b) Ionization measurements can be made in this type of chamber with more precision than in other kinds of chambers.
 - (c) The use of electronegative gases to reduce significantly the sensitive time of the chamber¹² does not adversely affect the track characteristics.

Disadvantages of operation in the streamer mode are:

- 1) The light output is so low that photography presents serious problems.
- 2) Very high voltages are required, and operating conditions are relatively critical.
- 3) The intermittent nature of the tracks is not completely compatible with present automatic spark-chamber scanning systems.

Pulse Characteristics

For a given streamer length the brightness of the luminous centers increases rapidly with the electric field strength ($\sim E^2$).^{11, 12} The brightness does not depend sensitively on the pulse length, but spatially short streamers require a short pulse length. Figure 3 shows a high-voltage pulser designed to provide short pulses at high voltage.¹² The Marx generator, which has a relatively high internal impedance, is used only as a voltage source for the low-impedance pulser consisting of C_1 and the series spark gap, which is set to fire near the top of the applied voltage pulse. Through resonant charging, twice the voltage of the Marx generator is available at the load. The pulse is kept short by use of the shorting gap which is prepared by an early trigger and fires about 10 ns after the voltage on the chamber rises. If the chamber is physically long, or if it is supplied by a long transmission line, it is important that a termination be used to prevent reflections.

Track Brightness

The limited brightness of tracks in streamer chambers can be handled either with large-aperture lenses ($\approx f/2$) and fast film (ASA ≈ 3000), or with image intensifiers. In the former cases, depth of focus and film resolution limit the precision attainable. In the latter case there are serious distortion problems and loss of resolution. Using a 3.5-in. -diam. two-stage tube [RCA (C70012),

gain ~ 1500 , resolution 25 lines/mm], Bulos et al.¹² find an effective optical gain of 12. Jones and Loo have successfully used a three-stage tube [RCA (C73491), gain $\approx 30,000$, resolution ≈ 15 lines/mm] with a small streamer chamber.¹³

Momentum-Measurement Precision

In the wide-gap streamer chamber, measurement precision is ultimately limited, as it is in the wide-gap spark chamber, by the incoherent displacements of the luminous centers from the particle trajectory. The rms displacement of these centers is ~ 0.2 to 0.3 mm.^{12, 14} From this and the average density of such centers, it is inferred that the highest measurable momentum (normalized to a 1-m gap in a magnetic field of 10^4 Oersteds) is 400 MeV/c for either the spark or streamer mode.^{14, 12, 2} In practice, then, for those events where the use of either mode is possible, the streamer mode would tend to give less precise momentum measurements, because of the difficulties of recording the track.

Ionization Measurements

Differences in primary ionization are easily recognizable in streamer chambers, but precise measurement is hindered by saturation effects. That these effects exist is clear from the fact that for minimum ionizing particles only a few luminous centers per cm are ordinarily observed, although the number of initial ion pairs may be an order of magnitude greater. A statistical model for the development of streamer tracks has been presented by Chikovani et al.,¹⁴ and systematic measurements have been made by the SLAC¹² and Erevan^{15, 2} groups. A strong correlation is found between specific ionization and either streamer brightness, streamer density, or streamer length for $1/I_{\min}$ up to about six.^{15, 2} It was observed by Bulos et al.¹² that delaying the pulse by a few microseconds leads to the production of twice as many luminous centers. This is a consequence of the reduced effect of robbing by adjacent streamers after prolonged diffusion of electrons from the track.

IV. Microwave Discharge Chamber

Following a long history of only limited success in the detection of charged particles in microwave chambers,^{16, 18} a very impressive result has been obtained recently.^{19, 20} Figure 4 shows cosmic-ray tracks obtained in a 2.2 by 4.7-cm waveguide chamber operating at 5550 MHz in the TE₁₀ mode, with a 0.1- μ s pulse from the 250-kW (peak) magnetron terminated in a dummy load. The chamber gas is neon with 1% argon and 0.1% alcohol at 500 mm pressure. For correct operation, the field strength must be constant. To achieve this condition, the pattern of discharge in the gas can be used as a tuning indicator.

In performance, the microwave chamber resembles the streamer chamber. With a minimum delay in application of the pulse, the number

of developed streamers is much less than the number of primary ions, and saturation effects hinder accurate ionization measurements. With the pulse delayed, however, the number of developed streamers is increased, and individual spot sizes ≤ 1 mm are observed.

Although the optical system is not described, we may assume that it resembles that used in earlier tests with a similar setup, i. e., an $f/2.8$ lens with Japanese SSS film (corresponding roughly to American XXX).¹⁷ It would appear therefore that the brightness of the microwave streamers is somewhat greater than that now attainable in ordinary streamer chambers.

To have much practical use, the microwave chamber should be made in volumes larger than that shown in Fig. 4. The prospect of a chamber made up of waveguide sections laid side by side is not very attractive for obvious reasons. It has been suggested that a circularly polarized mode of lower frequency could be used in a larger chamber.¹⁷ Another way would use incoherent filling of a large volume.²¹ In this connection the new results are encouraging. First, the microwave power used is less by about two orders of magnitude than that available from presently tested high-power sources, and second, the pulse length (0.1 μ s), about an order of magnitude longer than that used in the best operation of ordinary streamer chambers, is long enough to suggest the feasibility of incoherent filling of even a relatively large volume.

V. Narrow-Gap Chambers

Spark-chamber-oriented research programs in particle physics still depend almost exclusively upon the use of narrow-gap chambers. The reasons are partly historical, but also emphasize the simplicity of use, both during the experimental run and in the analysis of data.

Measurement Precision

With optical methods, as well as with a variety of "filmless" techniques, it has been shown that the rms deviation of sparks from a track essentially normal to the electrodes is approximately 0.25 mm. This compares well with the value for track displacement and luminous-streamer displacement found for the wide-gap spark and streamer chambers described above. These results are all compatible if it is assumed that spark development generally proceeds from isolated, well-developed streamer centers.

Self-Supporting Low Density Electrodes

Low-density electrodes without need for the usual heavy supporting picture frame promise to have many applications. As developed at ANL,²² electrodes with a thickness of 15 to 20 mg/cm² (aluminum equivalent) are made of thin foil glued to polyurethane foam sheets to form a rigid structure of thickness (3 mm) sufficient to avoid edge sparking. Tests at ANL and LRL²³ have revealed the need for care in sealing the electrode

structure to avoid excessive contamination of the chamber gas by Freon, a highly electronegative gas used in fabrication of the polyurethane foam.

"Hydrogen" Chambers

The desirability of hydrogen as a target material has prompted experiments to measure its effectiveness as a spark-chamber gas; tracks have been observed at Dubna²⁴ and at LRL.²⁵ In a related experiment helium at a density appropriate to operation in intimate contact with liquid hydrogen has been found to give excellent performance.²⁵

Chambers for Filmless Techniques^{26, 27}

Many of the recent developments in narrow-gap spark chambers are especially relevant to the needs of filmless techniques, which now depend entirely on narrow-gap chambers. Filmless methods are adaptable to a variety of geometries and in many cases can provide a much better means of data extraction. For cylindrical geometry, for example, both acoustic²⁸ and current-ratio²⁹ devices have been used. Such devices can, in principle, provide better methods for obtaining stereo information than the awkward and difficult optical systems used until now.^{30, 32}

For chambers using wire arrays for electrodes, a low-density cloth, woven with copper wires running in one direction and organic fibers in the other, is now commercially available in the U. S. A. and Europe. Wire mesh is also available for chambers whose operation depends upon the measurement of current.³³

VI. Spark-Chamber Data: Automatic Analysis of Film

The general use of film to record spark-chamber data has led to the development of a variety of automatic scanning and measuring systems.^{34, 27} In some cases the development of devices for bubble-chamber film scanning has been particularly useful.³⁵ In almost all automatic systems, a light spot is imaged on the film, and the local transparency is measured with a photomultiplier tube. Motion of the spot relative to the film, performed either mechanically or electrically, is digitized. When a "hit", or abrupt change in transparency indicating either a spark or fiducial, occurs, the relative position of the spot is recorded.

Mechanical Scanners

(1) The HPD (Hough-Powell Digitizer) at CERN produces a raster scan with orthogonal motion of film and light spot.³⁵ Calibration by means of a synchronized precision grating counter gives a measurement precision of $\sim 4\mu$ in the film plane. The "hit" information is sent for storage on-line to a large computer, IBM 7090 (CDC 6600).³⁶

(2) A similar device at BNL has no on-line computer.³⁷ It uses magnetic tape for storage.

(3) The Cornell automatic scanner uses a moving film with fixed light source and optical system.³⁸ With the film moving at constant speed parallel to the spark-chamber plates, a spark is recorded in terms of the time its image passes a fixed (photodiode) sensor. Precision, based on interpolation between grid lines in the spark-chamber space, is about 25μ on the film. Storage is on punch cards or magnetic tape.

Cathode-Ray-Tube Scanners

As the source of a well-defined light spot ($\approx 25\text{-}\mu$ diam), the precision CRT provides some advantages in flexibility over the mechanical devices, for which the scanning mode is severely constrained by mechanical inertia. The ways in which this flexibility is used characterize the various CRT systems. Although many of these systems do not approach the HPD in precision, it is quite feasible with care in the electronics to have a CRT system with open-loop reproducibility and short-term stability of the order of one part in 10^4 . Experimental errors from other sources often exceed this by a significant factor. The nonlinearities of the CRT system are of the order of 1% or larger, but usually this is no worse than that of the spark-chamber optical system ahead of the film, and corrections must be made for distortions in any case.

(1) Luciole at CERN is an electronic analogue of the HPD.³⁹ It produces a raster scan of the film and feeds spark coordinates on-line to a large computer. With a grid inserted temporarily, the scanning raster is periodically recalibrated. Although the computer is not used to control the scanning pattern, present plans include addition of a computer (CDC 6600) feedback link to control the transmission of data.

(2) SAMM at Columbia scans chamber gaps oriented parallel to the x-axis, with some arbitrariness in the y spacing of the gaps.⁴⁰ Digitizing is done with a split light beam, scanning simultaneously the film and an optical grating which controls a pulse counter. The digitized coordinates are recorded on tape.

(3) CHLOE at ANL uses a restricted raster scan under control of a small computer (ASI 210).⁴¹ Recognition of sparks and fiducials, now done on a large computer (CDC 3600), will eventually be carried out on the ASI 210.

(4) ARIANE at Orsay uses a combination of computer control (CDC 160A) and track following, with direct feedback from fiducials on the film to guide the scan.⁴² The precision depends upon interpolation between fiducials. Digitized coordinates are recorded on magnetic tape.

(5) The University of Michigan programmed spot scanner (Fig. 5) is under control of a PDP-1 computer, which plots each point along the scan

according to a prepared numerical table of chamber gap coordinates.⁴³ Scanning proceeds along the center of each gap, and detected sparks are recorded on magnetic tape for processing on an IBM 7090 computer.

(6) SPASS at MIT is a more fully programmed scanner, also controlled by a PDP-1 computer.⁴⁴ In this case each detected spark is evaluated immediately, and subsequent scanning is guided to provide on-line track reconstruction.

(7) SASS at LRL is conceptually similar to SPASS, using, however, a slightly larger computer (Computer Control Company DDP-24) and a CRT of higher resolution.⁴⁵

(8) After rather simple modifications, various Vidicon systems (Section VII) are capable of scanning film. Using a simple lens system to project the spark-chamber photograph onto the cathode of the Vidicon permits spark information to be digitized in terms of the position of the electron beam in the Vidicon. The Vidicon is less precise by about an order of magnitude than a good precision CRT.

There seems to be general agreement that in an overall sense the programming needs are similar for all flying-spot systems.²⁷ The more fully programmed-spot systems have the disadvantage of requiring relatively more programming in machine language (for the small computers). However they provide a more convenient framework for rapid feedback to check the overall performance of the system. An additional advantage of the programmed-spot system is in connection with experiments producing many frames, of which only a small percentage are useful, and where only a small fraction of the film format needs to be scanned in order to determine, by pattern recognition, that a given frame is useful. Until now, few experiments undergoing automatic analysis have fulfilled such conditions.

VII. Spark-Chamber Data: Filmless Methods

Film is used by most groups doing spark-chamber experiments in particle physics, but there is a growing interest in the filmless methods which provide direct electrical readout of spark-chamber data.^{26, 27} Ordinarily this requires a buffer-storage system followed by a "permanent" storage medium like magnetic or paper tape. Or, alternatively, the data may be sent to a computer for on-line processing. Details of the interfacing, storage, and computer use will not be considered here.

Briefly the currently most important filmless techniques are:

1. Wire-Magnetic Core. Each wire of an array forming an electrode of a narrow-gap chamber is threaded through a magnetic core which is interrogated after being set by the spark current. Such systems have been developed

at BNL, Chicago, Harvard, and CERN.^{26, 27}

2. Current Ratio. The ratio of the difference divided by the sum of the spark currents to two edges of a chamber electrode is equal to the negative of the corresponding ratio of the resistances from the spark to the same edges. If parallel wires (or a rectangular wire mesh) are used for the electrode, this ratio, for opposite edges, is a linear function of the spark coordinate perpendicular to those edges. (CERN,³³ Orsay,⁴⁶ and Lyon²⁹)

3. Vidicon. The spark-chamber image, projected onto the Vidicon photocathode, is scanned by the electron beam. The digitized position of the beam is recorded whenever a spark is detected. (LRL, Princeton, Chicago, Harvard, and Lund^{26, 27})

4. Sonic or Acoustic. The sound emitted by the spark is propagated through the gas at constant velocity. The time of flight to several (usually four) transducer probes is digitized and used to locate the spark in both x and y. (BNL, CERN Columbia, Rutherford, Liverpool, and Rome^{26, 27})

5. Magnetostrictive. All wires of an array forming a chamber electrode lie across a magnetostrictive wire (e.g., nickel). The digitized time of transit of the spark-induced acoustic wave to a sensing element outside the chamber gives one coordinate of the spark. The other coordinate may be determined similarly using the other electrode of the gap or alternatively, the current ratio between signals picked up from magnetostrictive elements at both ends of the wires on one electrode can be used. (LRL and Bari^{26, 27})

In Table I the filmless methods are compared with respect to properties important in experimental physics. Obviously such a table tends to over-simplify, and many assumptions must be made. Some of these are indicated in the footnotes to the table. Others are as follows:

Cost

Costs and construction time have been neglected because accurate estimates are hard to get and because construction practice differs greatly at different laboratories for a given type of chamber.

Chamber Size

Two sizes are considered because different types of chambers scale differently. In general the digitized wire chamber is more difficult to scale up in size than those systems with an analogue stage. On the other hand, the precision of the analogue devices has been checked only to about one part in 10^3 . Another order of magnitude in precision is probably available, but more care must then be taken in calibration. The current-ratio chamber suffers somewhat in precision relative to the others, partly because of end effects.

Wire Spacing

For the core system, the assumed wire spacing of 1 mm limits the precision relative to

TABLE I. Comparison of filmless spark-chamber techniques.

Chamber size		2 meters					0.2 meters ^(a)				
Chamber type		Wire-core	Current ratio	Vidicon	Sonic	Magnetostriction	Wire-core	Current ratio	Vidicon	Sonic	Magnetostriction
Recovery time	(ms)	≤ 1	≤ 1	≥ 30	10	≤ 1				5	
Precision	(mm)	0.5 ^(b)	2-20	2 ^(c)	<2	< 2	0.2-2 ^(d)	0.2 ^(d)		<0.2 ^(d)	<0.2 ^(d)
Two-spark resolution	(mm)	3	—	8	25 ^(e)	2			0.8 ^(f)		
Minimum readout time	(sec)	$5 \cdot 10^{-8}$	$5 \cdot 10^{-8}$	10^{-4}	$6 \cdot 10^{-3}$	$4 \cdot 10^{-4}$				$6 \cdot 10^{-4}$	$4 \cdot 10^{-5}$
Multispark capability		Good	No	Excellent	Poor ^(g)	Good					
Relative matter density		2	1	1	1	1					
Operation in 20-kG field		Yes ^(h)	Yes	Yes	Yes	Yes ⁽ⁱ⁾					
Use with wide gaps		No	No	Yes	No	No					
Use for scanning film		No	No	Yes	No	No					

(a) Data is not given for the 0.2-m chamber unless it is different from that for the 2-m chamber.

(b) A wire spacing of 1 mm is assumed.

(c) A precision of 1/1000 and resolution of 1/250 is assumed.

(d) A single spark cannot locate the track more closely than 0.25 mm.

(e) D. Freytag, A. V. Smith, G. Lavevière, "A System to Detect Several Sparks in a Sonic Spark Chamber", CERN 65-19, May 24, 1965.

(f) Ordinarily sparks are about 1 mm or more in width.

(g) It is difficult to detect two sparks in a sonic chamber because of chamber noise and reflections. More than two sparks is, for practical purposes, impossible. See reference in footnote (e).

(h) Bruce Sherwood, IEEE Trans. Nucl. Sci. 12, 4 (1965). The cores would saturate in the field, but they may be displaced to a remote position with the use of electrical interfacing.

(i) V. Perez-Mendez, private communication. At high fields a few percent of the zero-field signal can be obtained and is sufficient.

analogue devices, for which current sharing between wires better preserves the spark centroid. Closer spacing in a core system is certainly feasible if it is required.

Emphasis of Particular Characteristics

Operation which is simultaneously optimum in all properties is not possible. For example, reduction of spark energy tends to improve spatial resolution at the expense of efficiency.

Conclusions from Table I

The need for fast on-line signals for logical use in triggering other chambers can justify the development of the wire - core and current-ratio chambers. The Vidicon system can perhaps survive because of applications to film scanning and anticipated future use with wide-gap chambers. The magnetostrictive chamber rates high in all categories, and is probably the best all-around filmless device. The only system for which extensive future development seems hard to justify is the sonic chamber, which, ironically, has been the one used most in filmless spark-chamber applications to particle-physics research.

VIII. Spark-Chamber Trigger Logic

Use of Spark Chambers

The development of spark chambers with prompt electrical readout and short recovery time has led to the use of such chambers in the trigger circuitry for larger or more slowly recovering chambers. Figure 6a shows the use of five current-ratio chambers in an experiment requiring range measurements on two secondary particles.⁴⁷ In the absence of kinematical information derived from the current-ratio chambers, the experimental background would have limited the effective data rate because of the rather long recharge time needed for the range chambers.

Figure 6b shows a different type of experiment, for which the background was reduced by an order of magnitude with a wire - magnetic-core chamber.⁴⁸ With the cores used as discriminators, a pulse out of the chamber could be obtained within 50 ns of the spark time. The chamber output was used to require that two charged particles enter the analyzing system. Relatively poor spatial resolution was sufficient; the need in this case was for a low-density detector to reject background produced by γ -ray conversion in the detection system.

Although the wire - magnetic-core chamber can be pulsed comfortably at rates of 1 kHz, a low-density detector with even higher rate capabilities would be useful. Roddick and Koester have tested a wire array designed for operation in the proportional mode.⁴⁹ A recovery time less than 5 μ s was measured. The only practical difficulty in the use of such an array is the small pulse height (≥ 5 mV) which, it is suggested, could be offset with an integrated circuit pre-

amplifier for each wire.

Use of Counters

Without careful counter control, most spark-chamber experiments would be reduced to the status of second-rate bubble-chamber experiments. Figure 7 shows a carefully designed trigger system using scintillator hodoscopes and Cerenkov counters to detect the annihilation of an antiproton-proton (pp) pair into two light particles.⁵⁰ Experimentally, it was important to reject elastic scattering, which dominates the $\pi\pi$ final state by a factor of 500 and the ee final state by a factor of 10^8 . The electron-positron events were separated from the pions and kaons with the help of the shower chambers and Cerenkov counters. In order to separate all these lighter particles from the pp final state, the angle of each secondary with respect to the well-defined beam direction was measured with counter hodoscopes. (Orthogonal-coplanarity hodoscopes helped to reduce background from final states with more than two particles.) This information was digested in a small homemade computer, which consisted of digitizers, adders, and a coincidence matrix to relate the differences of the hodoscope counter coordinates. In the final matrix, only those coincidences that corresponded approximately to the appropriate kinematical relationship were accepted for the spark-chamber trigger logic. At the same time an on-line commercial computer (PDP-5) performed housekeeping functions and accumulated data on the basis of the hodoscope information.

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MUB-9850

Fig. 1. Schematic drawing of a wide-gap spark chamber with two gaps.
The performance is described in the text.

ZN-5424

Fig. 2. From reference 10. Ninety-degree stereo views of a double-prong event in a spark chamber with a 40-cm-wide gap. A neutral beam entered through the electrode crossed by the charged particles. The chamber was operated at 400 keV with a 0.16- μ sec pulse. The photographs were made with Kodak 35-mm Tri-X film and a lens opening of f/11.

MUB-9853

Fig. 3. From reference 12. (a) Pulse generator to supply very-high-voltage short pulses to the streamer chamber, and (b) pulsed high-voltage power supply for the pulse generator. (See text.)

ZN-5425

Fig. 4. From reference 20. Tracks travelling transverse to the electric field in a microwave chamber. Track (a) is of a relativistic electron, track (b) is of a 120-MeV proton, and track (c) is of a 30-MeV proton.

MUB-9851

Fig. 5. From reference 43. The light spot on the face of the CRT is controlled in position by a PDP-1 computer. It is focussed onto the film, of which the local transparency is measured by the detector photomultiplier. Use of optical beam splitters provides for use of a reference photomultiplier, for scanning another film in parallel, if desired, and for direct observation of the film on a viewing screen.

MUB-9854

Fig. 6. Schematic diagrams of uses of decision-making spark chamber. (a) From reference 47. Protons produced in the lithium target by the reaction $\pi^+ + \text{Li}^6 \rightarrow \text{He}^4 + p + p$ are stopped in the range chambers R_1 and R_2 . C_1 through C_6 are scintillators. The function of the "decision-making" current-ratio chambers L_1 through L_5 is described in the text. (b) From reference 48. Electrons from the decay $\mu^- \rightarrow e^- + \nu + \bar{\nu}$ are analyzed for polarization by scattering in a magnetized iron foil. Similarly, positrons are obtained from $\pi^+ \rightarrow \nu_1 + \mu^+ \rightarrow \nu_1 + \nu + \bar{\nu} + e^+$. H and V are respectively horizontal and vertical scintillator hodoscopes; C_1 , C_2 , and C_3 are scintillators; L_2 is a thin-aluminum-electrode chamber; and L_3 is a range chamber. The function of the digitized wire - magnetic-core chamber L_1 is described in the text.

MUB-9852

Fig. 7. From reference 50. Schematic diagram of the Caltech-BNL $p + \bar{p} \rightarrow e + \bar{e}$ experiment. Use of hodoscope counters give sufficient kinematical information to reject elastically scattered antiproton events and to select those events with two lighter particles in the final state. Use of spark-chamber and Cerenkov-counter information permits sorting of the lighter particles, e.g., π , K, and e.

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