RECENT TRENDS IN PARTICLE DETECTION AT HIGH ENERGIES *

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The main objective in carrying out an experiment in particle physics usually consists of studying a particular interaction process or of determining certain characteristics of a particle or state. This generally requires the detection and identification of the particles involved, the measurement of their momenta, directions of flight and other pertinent information as desired.

As the energy of the particle is increased, or if the beam intensity is raised considerably, the detection problem becomes more difficult and often considerably more complicated. For instance, when the particle energy extends into the relativistic region, not only its identification, but the momentum measurements and separation of desired particles from undesired ones, become increasingly difficult. However, in the past few years tremendous strides have been made in the various detection techniques at high energies. I shall briefly review some of the recent developments and the general trends of particle detection at high energies.

Before doing this, I shall mention another aspect of detection problems which has become increasingly important as we go to higher energies. This concerns the effective utilization of high energy accelerators.

As we know, the tremendous interest shown in high energy research has resulted in a constant overflow of experimental proposals at the highest energy accelerators in existence today. Unfortunately, the available machine time in these accelerators falls far short of adequately satisfying these demands. It has become essential to seek ways of improving the efficient utilization of these machines. Significant success has already been achieved in the direction of scheduling several experiments simultaneously. As an example, as many as five separate experiments have been carried out successfully at the Brookhaven AGS

by proper programming of multiple targets and by appropriate sharing of beams from these targets. Remarkable success has also been achieved in the efficient use of detection techniques, i.e., by the maximum utilization of high intensity beams available through proper design of the experiment so that the detection system is capable of making use of all the desired particles contained in the beam; it must also cover as much of a useful solid angle as feasible, so as to detect the maximum number of interesting interactions involved. An example of this is the high energy elastic scattering experiments performed with high precision at Brookhaven, where a system of counter hodoscopes (1) (multi-counter arrays) was successfully used with automatic data handling and on-line computer analysis with immediate feedback of analyzed results to the experimenters. The present system at Brookhaven is capable of handling one million events per hour and can be further expanded if necessity demands it. Due to these new techniques, up to two orders of magnitude increase in data accumulation rate was possible, accompanied by a higher systematic accuracy than previously attained, and for the first time a wide survey of the field was practical in one experimental run. The automatic data handling and on-line computer analysis system is equally applicable to sonic or wire spark chambers, and has proved so successful that it is now widely used in many laboratories. A good example of such on application to spark chamber experiment was illustrated yesterday by Dr. Maglio.

Similarly, for bubble chamber photograph analysis, the successful development of measuring devices on-line to computers is expected to reach a capacity of about 10,000 events per week. An eventual rate of 100,000 events per week may be within possibility, especially when problems concerning automatic « pattern recognition » can be solved.

It is obvious that the great advantage of the above-mentioned system in obtaining maximum

utilization of the high intensity beams of a high energy accelerator would certainly make it even more desirable when much demanded super high energy accelerators of the order of hundreds of BeV are built.

Generally speaking, as the nature of investigations in high energy experiments becomes more exacting and often more sophisticated, data with high precision, low background and under more exacting conditions are usually required. Thus, the generally desirable features of high energy detectors are, for example, good space and angular resolutions, precise momentum analysis, large interaction volume, fast time resolution, good particle identification, efficient data gathering power, on-line computer data analysis, etc.

I shall now present, very briefly, my impressions of the recent trends in the various detection methods at high energies.

I. BUBBLE CHAMBER (2)

As we are all familiar that charged particles give rise to visual tracks when they traverse the liquid medium of the chamber. One excellent feature of the bubble chamber is that it is capable, if its size is large enough, to present a complete reaction process in a single picture which allows us to study the whole reaction. Another valuable feature of the bubble chamber is its good space resolution. With existing chambers such as the 80 inch chamber one can count on obtaining tracks of 1 m lengths or more. Sagittas of curve tracks can be measured with accuracies approaching 25 μ in the chamber space. Magnetic fields are of the order of 20 kG, which gives an accuracy in the momentum measurement for a, say, 5 BeV/c track, much better than the accuracy limit imposed by the multiple Coulomb scattering. This is also sufficient to measure the momentum
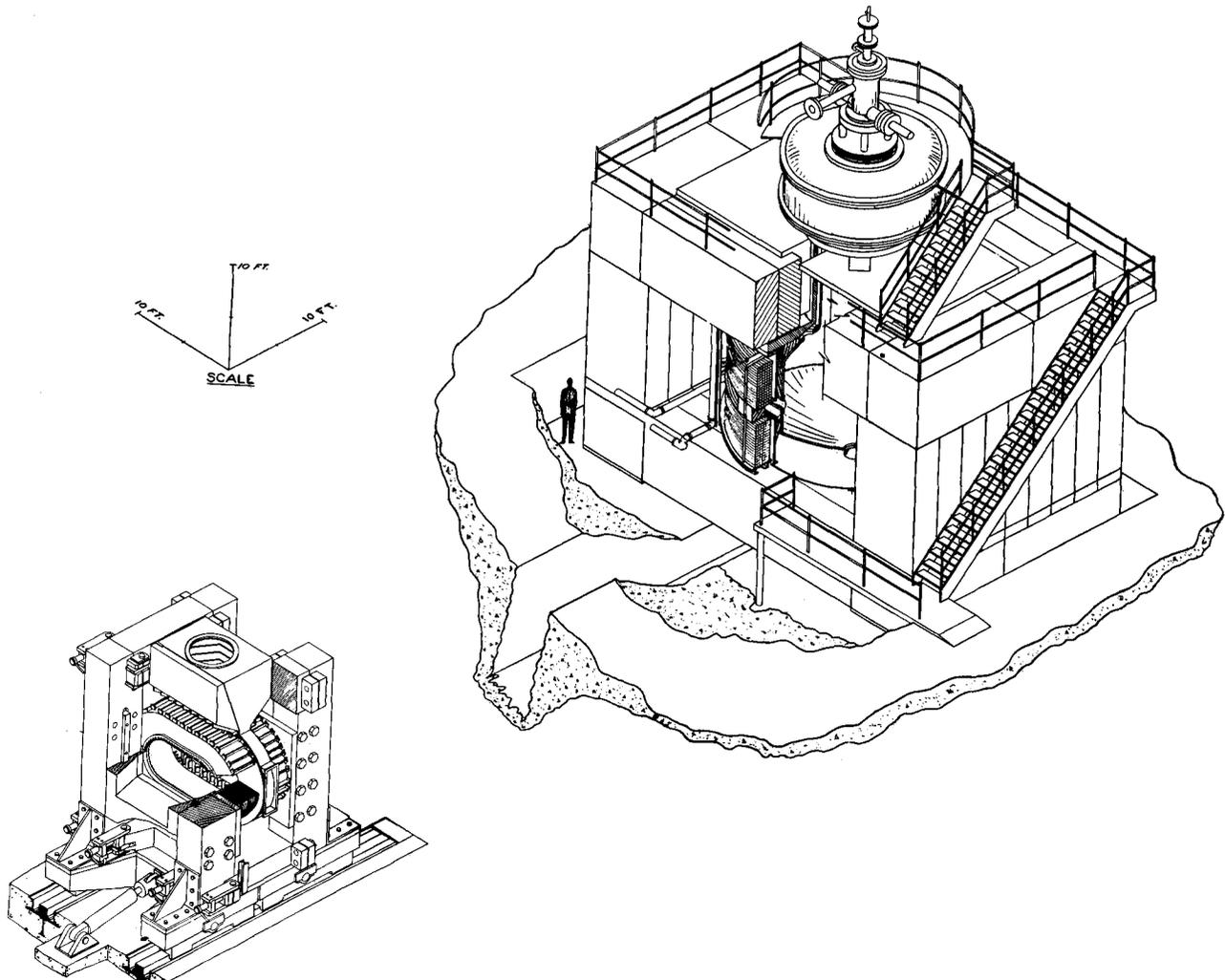

Fig. 1 - An artist's drawing of the 14 ft. liquid hydrogen bubble chamber proposed by Brookhaven National Laboratory. For comparison, at the lower left, the BNL 80 in. chamber is also shown.
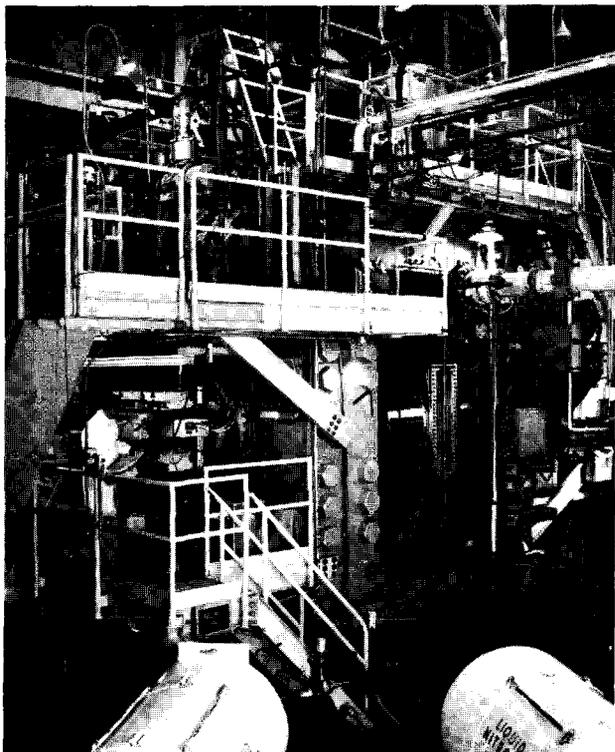
Fig. 2 - BNL 80 in. liquid hydrogen bubble chamber.

of a 100 BeV track with 3% accuracy. The recent success in obtaining fields of 100 kG or more with super conducting coils may make it possible to measure a 500 BeV track with an accuracy about equal to the limit given by multiple Coulomb scattering.

A high energy proton traversing a liquid hydrogen bubble chamber will, on the average, collide with a target proton once in every 25 feet of track length (assuming a cross section of 40 millibarns). Rare events with cross sections of the order of a few microbarns occur a few times per 1,000,000 feet of track. Collisions due to neutrinos are even rarer by a factor of about 200,000,000 (cross section 5×10^{-39} cm^2). In the Brookhaven 80-inch liquid hydrogen bubble chamber, it takes about 10,000 photographs with 15 charged beam particles in each photograph to obtain 1,000,000 feet of track length. One can immediately see the need to go to larger size chambers in order to make the difficult experiments mentioned above more feasible.

Another direction one can go to gain the event rate is to increase the number of bubble chamber photographs per unit time. As an example, if one can increase the picture taking rate from one per three seconds to three per second, one would gain a factor of nine in the event rate.

It is evident that the trend of the bubble cham-

ber technique goes in the direction of larger size, higher magnetic field and increased repetition rate.

A design for a 14 ft diameter liquid hydrogen bubble chamber has recently been proposed at Brookhaven for use at the AGS (2). Here the momentum accuracy will be improved considerably because of greater length of the tracks and very much improved for the particles that stop in the chamber. In the case of neutrino experiments, a 14 ft diameter chamber will increase detection capacity between 8 and 25 over the 80 inch chamber depending on the particular neutrino experiment considered. Fig. 1 shows an artists sketch of this chamber with a sketch of the present 80 inch chamber on the same side for comparison. A photograph, of the 80 inch chamber is shown in Fig. 2. A similar chamber, 12 ft in diameter, has also been proposed at Argonne National Laboratory, and preliminary considerations for a 20 ft diameter spherical liquid hydrogen and deuterium bubble chamber (6 tons of hydrogen) for use at the proposed 200 BeV accelerator have been contemplated at the Lawrence Radiation Laboratory.

Designs for a super conducting magnet with a field of 40-50 kG to be used with the proposed 14 ft chamber are now being studied at Brookhaven. Means for increasing the repetition rate of large bubble chambers, possibly by a factor of 5 over the present repetition rate, is also under investigation. A double-repetition-rate bubble chamber has been operating successfully at the Lawrence Radiation Laboratory.

II. CERENKOV COUNTER

As is well known, the angle θ of emission of the Cerenkov radiation caused by a traversing charged particle in a medium is given by

$$\cos \theta = 1/\beta n$$

where β is the velocity of the particle and n the index of refraction of the medium. For the iden-
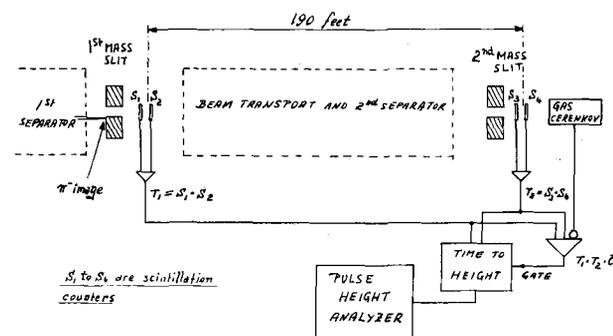

Fig. 3 - Schematic of the beam separator and time of flight system.

tification of particles in the very high momentum region, say for $\beta \geq .95$, a differential gas Cerenkov counter is extremely useful, especially since the momentum of the desired particle can be varied easily by varying the index of refraction, n, of the gas (simply by varying the gas pressure). However, there is a practical limitation on how high a pressure one can exert on a certain gas (i. e., how high an index of refraction can be reached) without converting the gas into liquid phase at normal operating temperatures. This limits essentially the usefulness of a gas Cerenkov counter for lower momentum particles, say kaons, to a momentum of not lower than 1.5 BeV/c. This fact, and the necessity of a wide momentum range of the desired particle (i. e., large variation in the index of refraction) led one to use a differential Cerenkov counter with liquid solutions as radiator for the low momentum particles. The refractive index of the radiator can be varied by changing the relative proportion of the components in the solution.

Because of the extremely high angular resolution obtainable in a differential type Cerenkov counter, it is widely used for particle selection, especially at high energies. The rejection ratio of undesired particles to the desired ones is exceedingly good in this type of Cerenkov detector. This rejection ratio can be considerably improved even further by making use of the Cerenkov radiation emitted from the undesired particles and employ it as an anti-coincidence signal. This feature is generally adopted in many experiments. When the momentum of the desired and the undesired particles both lie in the relativistic region, additional Cerenkov counters (either the differential type or the threshold type) are generally used in tandem to obtain adequate selection of the desired particles.

Ut to the highest energy available in present machines, the Cerenkov counter is still by far the best device for particle selection. Its time resolution is also exceedingly fast which, in practice, is limited mainly by the resolution time of the photomultipiler tube employed.

The incorporation of chromatic correction lenses (3) inside a differential Cerenkov counter can further increase the resolution by a factor of 15-20 and greatly improve the rejection ratio against the undesired background.

The tendency of the Cerenkov counter development seems to lie in the direction of increasing the resolution by means of optical improvements in the collection of the Cerenkov radiation, reducing the Cerenkov angle and increasing the radiation paths (longer counter length), improving the efficiency of the anti-coincidence feature, com-

bined usage of various types of Cerenkov counters, and so on.

Another aspect of Cerenkov counters which has great promising prospects for high energy application is the Cerenkov chamber. In such a chamber where the Cerenkov light emitted by a single particle traversing a radiator is imaged by means of a mirror or lens focussed at infinity onto the cathode of an image intensifier tube, the image is a ring whose diameter measures accurately the Cerenkov cone angle and thus the particle velocity. In addition, the coordinates of the center of the circular image accurately indicate the orientation of the particle trajectory (though not its position). Limitations on the intensity obtainable and the usable angular field of view would probably restrict its application to particles of momentum less than ~ 50 BeV/c.

III. TIME OF FLIGHT METHOD

Two recent applications of the time of flight technique to high energy experiments offer some interesting advantages. One of these is the time of flight measurement making use of the r.f. structure of the beam; another is the combination of beam separation technique and time of flight measurement.

— *Time of flight measurement using the r.f. structure of beam.* If, at the end of the accelerating cycle, the internal proton beam is still strongly coupled to the r.f. voltage, then the circulating protons would strike the target in r.f. bunches. This is true also for the secondary beam from the target. If each r.f. bunch is narrow enough, a time of flight measurement can easily be made using the r.f. as a timing signal from the target. This technique has been used successfully by Piroue et al. (4) at the Princeton-Pennsylvania Accelerator in a recent experiment in which kaons produced in p-p collisions were detected over a wide momentum range (350-1300 MeV/c), using only time of flight techniques and momentum analysis. This method has the advantage of eliminating any momentum dependence of the kaon detection efficiency while keeping the background low, and it has some promising possibilities in high energy applications.

— *Combined beam separator method and time of flight measurements.* This is an extremely useful method in the search for heavy particles of unknown mass. Even though the mass range that can be explored in one setting is very large, a precise measurement of the mass can be obtained with this method. If the searched-for particle is a rare particle, i. e., if its abundance is of the order of only a few parts in a million or less, one
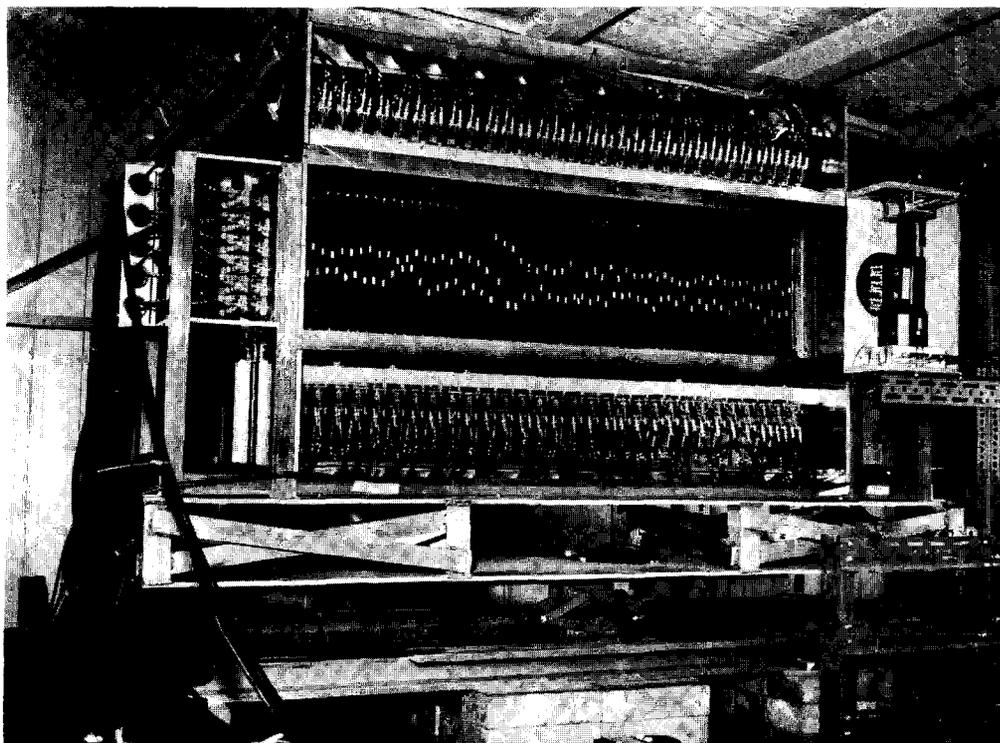
Fig. 4 - A counter hodo-scope assembly used in the recent BNL small angle elastic scattering experiment. This assembly consists of 120 vertical scintillator elements (0.486 in. wide, 13 in. long) and 24 horizontal elements (0.486 in. wide, 61 in. long).

can avoid the accidental counts by separating out from the beam the very abundant light particles (pions) by using a high energy separated beam ordinarily reserved only for bubble chamber experiments. In a recent experiment at the Brookhaven AGS by Franzini et al. (5) in the search for heavy triplets as conjectured by Gursey, Lee and Nauenberg (6), this method was used very successfully in carrying out such a difficult experiment which requires a rejection ratio of the order of 10^{-9}. Although no heavy triplets were found in the available energy range of the existing accelerator, it has established the encouraging fact that this method has proved to possess great potentialities and can be very useful for future applications of a similar nature at higher energies. Fig. 3 shows the arrangement of such a scheme. The first separator was so adjusted as not to let negative pions and antiprotons go through the first mass slit. This arrangement alone gave a rejection of pions by ~ 10^{-4}.

The light particles were further rejected by a gas Cerenkov counter. The remaining particles going through the system were detected by two telescopes, T_1, T_2, each composed of two scintillation counters connected in coincidence and placed approximately one foot apart. The time lag between the signals from T_1 and T_2 was measured with conventional time to pulse height converter and pulse height analyzer. The time measurement resolution is better than 1 nsec.

The beam momentum was set at 7 BeV/c over a path of 190 ft; the time of flight for a 4 BeV particle is 29 nsec longer than for a pion. The total rejection for pions versus particles of 4 BeV mass was about 10^9 and the percentage error on the mass was given by $dm/m \approx 3\%$.

IV. SCINTILLATION HODOSCOPE AND ON-LINE COMPUTER METHOD (1)

This method was first used by our group at Brookhaven in 1961 and was used successfully to investigate the elastic scattering of various elementary particles by protons. The unqualified success of this method and its many advantages, especially the on-line computer technique, has opened up a new avenue in counter and spark chamber experiments. Fig. 4 shows one of the hodoscopes used in such a system.

Because of the extremely fast time resolution of scintillators, scintillation hodoscopes offer much greater advantages when large statistics or high counting rates are required. Although the space resolution of sonic spark chambers or wire chambers is extremely good, say ~ 1 mm in most cases, we have recently developed a hodoscope with much smaller elements which can give a space resolution of 3 mm. This is within a factor of 3 of

the space resolution of the wire or sonic spark chambers, whereas the angular resolution can be made comparable by extension of path lengths. Fig. 5 shows such a hodoscope element, together with a new smaller size photo tube (7767) and a newly designed thin baseboard which can be conveniently stacked without taking much space.

It is evident that a combined system of scintillation hodoscope and wire or sonic spark chamber with on-line data analysis would be an extremely useful and valuable technique. Wherever high flux measurements are required, such as in a high intensity beam, a high resolution hodoscope should be used, and where high space resolution is needed but event rate is low, a spark chamber system would be advantageous.

V. SPARK CHAMBERS AND WIRE CHAMBERS

A spark chamber, in its usual form, consists of thin parallel conducting plates separated by small gaps. The chamber is usually filled with neon or argon gas, and the adjacent plates are charged with a high electric field pulse which causes an electric discharge or spark to occur at the location where a high energy charged particle traverses.

A spark chamber has much better time reso-

lution than a bubble chamber, but perhaps not as good space resolution. It has better space resolution than electronic counters, but not as good time resolution. The resolving time is ~ 0.5 μsec for a plate spacing of 1 cm. The position of a spark can be measured to 0.25 mm in two dimensions and is determined by the plate spacing in the third dimension. For a chamber comprised of six 1 cm gaps, a typical measurement will give angles to an accuracy of ½° for tracks at 20° to the plates. A massive spark chamber as large as a good sized room containing many tons of material can be built without undue difficulty.

Because of its comparatively fast time resolution, a spark chamber is valuable when data collection by means of a bubble chamber becomes difficult. Its good space resolution makes it more advantageous than counters for use in experiments where large solid angle with good angular resolution is desired, but where the beam intensity requirement is not too high.

Recent developments in the sonic spark chamber technique, which uses acoustic detectors for defining the position of the spark, make it possible to digitize the location of the spark into a computing machine and thus lead to a rapid analysis of spark chamber data.

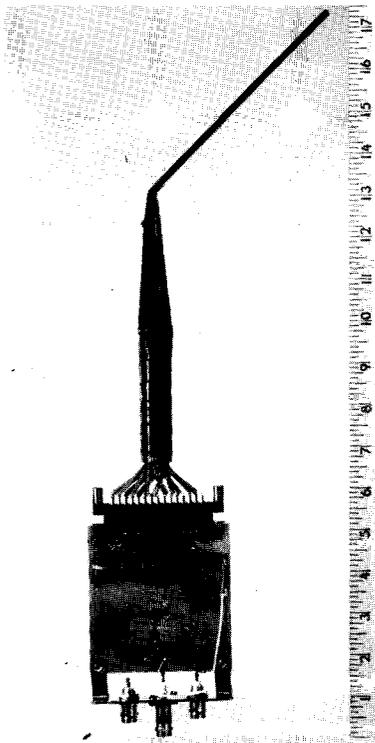Also, recent developments in the large gap spark

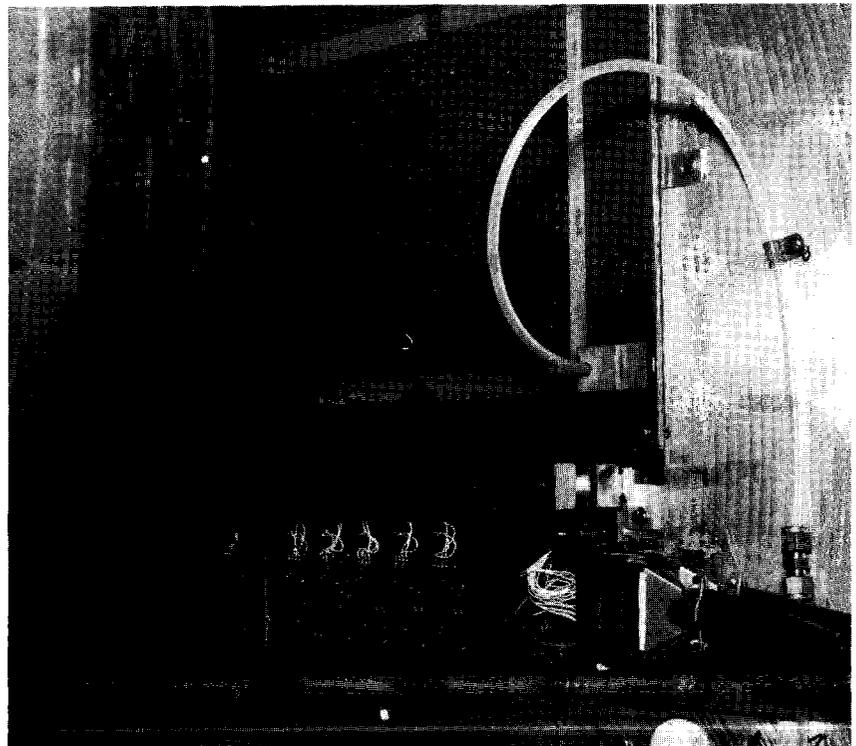Fig. 5 - 1/8 in. x 1/8 in. hodoscope element.

Fig. 6 - Wire spark chamber.

chamber (gap length ~ 40 cm) by Alikhanian (7) and his group at the Physics Institute of Yerevan show very promising characteristics for high energy applications. This type of chamber can give spark tracks following the path of a traversing charged particle like a cloud chamber up to an inclined angle of 40-50 degrees from the direction of the electric field. It is also called track spark chamber. One of its main advantages is that it can be placed in a magnetic field to give a curved track for momentum determination. Other major advantages are: high speed of operation, simplicity of design, high efficiency of detection (detection of electron showers of 50 particles showed close to 100% efficiency) and the possibility of detecting secondaries produced in the gas of the chamber. Some of the drawbacks of a track spark chamber are its comparatively large memory time (01. μsec), which limits the rate of data collection, and its incomplete 'isotropy", i. e., tracks when traversing at various angles to the direction of the electric field are not equal in luminousity.

Another recent development is the wire spark chamber, in which parallel conductive wires are closely spaced to form a wire plane, which replaces the conventional solid sheet plane. The wire chamber has even more encouraging prospects of useful applications of the spark chamber type of detector to high energy experimentation. Unlike the regular spark chamber or the sonic spark chamber, in which strong energetic sparks are needed to provide for their visual or acoustic detection, the wire chamber requires only a very feeble spark with just enough energy to set a magnetic core attached to the wire on which the spark took place, resulting in much faster recovery time (or the spark pulse can be stored in some memory device attached to the wires which can be read off at a later time). The information thus obtained is already digitized and can be easily fed into a digital computer, and a system of wire chambers will be able to define the space location of the particles under investigation to an accuracy of a fraction of 1 mm, which is the practical limit of the wire spacing.

A recent experiment (8) on the inelastic scattering of protons by protons at energies up to 30 BeV has been successfully performed at Brookhaven, using a series of wire spark chambers (actually printed wire planes). The sizes of the wire planes are 5" × 9" and 8" × 18" and wire spacing is 1/20". The space resolution of these chambers
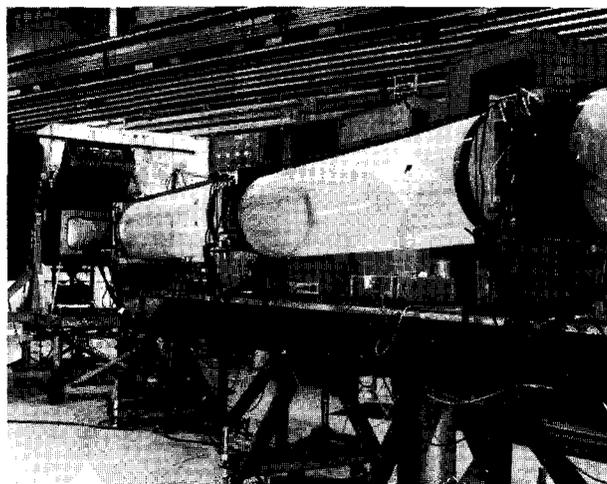

Fig. 7 - Experimental set-up using wire spark chamber and on-line computer system.

is slightly better than the wire spacing. The output of the wire planes is fed into an on-line computer similar to the system used in the scintillation hodoscope experiment mentioned above. Fig. 6 shows one of the wire spark chambers in place and Fig. 7 shows the experimental set up using wire spark chambers with on-line computer system.

A combined detection system using scintillation hodoscope, wire spark chamber and Cerenkov counters, each to serve an appropriate function with on-line data analysis, would be extremely useful in high energy applications.

So far I have mentioned the recent trends in particle detection at high energies employed successfully in various experiments. As we go into energies much higher than those available at the existing accelerators, say in the multi-hundred BeV region, the detection problem will become much more difficult, and new and improved detection techniques will be necessary. Some development and studies in this direction have shown encouraging indications, but I will not have time to go into them here. I will only mention that detectors using relativistic-rise effects (9) such as a Xenon gas scintillation counter, a secondary electron-emission counter, a solid state detector with internal pulse amplification, etc., show promising results, and the possible use of transition radiation (10) for the detection of particles in the relativistic region also gives encouraging indications.

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DISCUSSION

JONES: While I agree with all that Dr. Yuan has said, I was surprized at the omission of mention of photographic spark chambers coupled with automatic film analysis. Such systems are equivalent to wire or sonic chambers in their logic and systems organization, and it can be expected that photographic technique will continue to play an increasing role in more complex spark chamber experiments, for example those in which the trajectories of two or more particles must be followed through a magnet.

YUAN: I fully agree with you that photographic spark chambers coupled with film analysis will continue to play an important role in the future experiments, but the time of my presentation is extremely limited and I can only cover the more general aspects of the subject and cite the few cases which I personally feel can illustrate well the points I mentioned. I am sure that I left out many other specific cases of equal importance.

THE CPS IMPROVEMENT PROGRAMME

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INTRODUCTION

At the beginning of 1964 we began exploring possibilities to improve the CPS as an experimental facility. The improvements considered can be divided into two groups:

A. Increasing the CPS intensity
B. Extending the experimental areas.

A. PROJECTS TO INCREASE THE CPS INTENSITY

The maximum intensity of slightly above $1 \cdot 10^{12}$ protons/pulse is already limited by space charge effects and a further factor of two really seems to be the most that can be expected from the machine in its present state.

To raise the intensity above that limit, two projects are being studied: