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Jay N. Marx; David R. Nygren

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Detecting Particles

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Progress in experimental high-energy physics is limited in practice by two complementary aspects: the types of beam particles available with useful intensities and energies, and the characteristics of the detection techniques available for measuring needed information about collisions of interest and their subsequent reaction products. Most impressively, advances in accelerator design over the last three decades have led to an increase in beam energies of nearly three orders of magnitude, and the advent of colliding-beam machines has brought a comparable increase to the center-of-mass energy available. The diversity of useful beam species has now grown to include essentially all known particles with lifetimes greater than 10^{-11} seconds.

On the other hand, the number of well developed important fundamental techniques for particle detection and measurement has remained limited. In addition to continuously sensitive devices—such as photographic emulsions, Cerenkov, scintillation, ionization and drift-proportional wire detectors—triggered devices such as bubble, spark and streamer chambers essentially exhaust the list of commonly used techniques.

The challenge posed by this contrasting state of development is particularly evident in the design of experiments for the newest generation of electron-positron colliding beam machines such as PEP and PETRA. (PEP, being built at SLAC by Stanford and the Lawrence Berkeley Laboratory, stands for "Positron–Electron Project." PETRA, nearing completion at Hamburg, Germany, stands for "Positron-Electron Tandem Ring Accelerator." Both of these machines will provide center-of-mass energies in excess of 30 GeV.)

In these machines a single interesting collision may produce on the order of twenty charged and neutral particles, with a wide variety of interesting (and possibly new!) quantum numbers. To compound the difficulty, the distribution of particle trajectories is expected to be nearly isotropic when averaged over many events, but within a given event the trajectories may cluster together in a pronounced "jet" structure. This situation translates into an unusually demanding and conflicting set of requirements for detector performance, for which a completely satisfactory solution through conventional techniques does not appear to exist. The resultant frustration was the seedbed leading to the conception of the Time Projection Chamber idea.

The concept, known for convenience as the TPC, is based on the unusual parallel orientation of drift electric fields and magnetic fields; it is a new approach that simultaneously offers superior pattern recognition, particle identification, tracking and momentum measurement, all within a comparatively compact volume. By providing spatial data with an intrinsic three-dimensional quality, and as many as 200 space points per track, a new level of track-finding capability has been realized. A major new facility for PEP based on the TPC, now under construction, is scheduled for operation in mid-1980. A small prototype chamber has been in operation in a charged-particle beam for the past ten years, and has shown performance in agreement with expectations (figure 1).

PEP and PEP physics

The main component of PEP is a single ring of magnets enclosing a high-vacuum chamber through which counter-rotating beams of electrons and positrons circulate. The interaction of the circulating beams with the magnetic guide field leads to copious generation of synchrotron radiation, requiring several megawatts of radiofrequency accelerating power to maintain the circulating beams. Each beam is concentrated into three very short bunches and locked with the rf acceleration system so that beam–beam collisions occur only at six equally spaced "intersection regions" placed around the ring. The magnet ring itself is divided into six bending arcs connected by long straight sections passing through the intersection regions. This gives the ring a rounded hexagonal shape with an overall circumference of 2160 meters. Consequently, beam bunches pass through each other every 2.4 microseconds.

The event rates of interest, however, are quite small. The fundamental physics interest will presumably arise in electron–positron annihilation reactions, mediated by a single massive virtual photon intermediate state. Here the entire center-of-mass energy is converted to a large variety of final states, limited only by conservation laws governing interactions with photons as the intermediate state. To give some idea of rates, the number of

$$e^+ + e^- \rightarrow \gamma^* \rightarrow \mu^+ + \mu^-$$

The authors are both at Lawrence Berkeley Laboratory of the University of California; Jay N. Marx is a division fellow and staff scientist, and David R. Nygren is a senior staff scientist and group leader.

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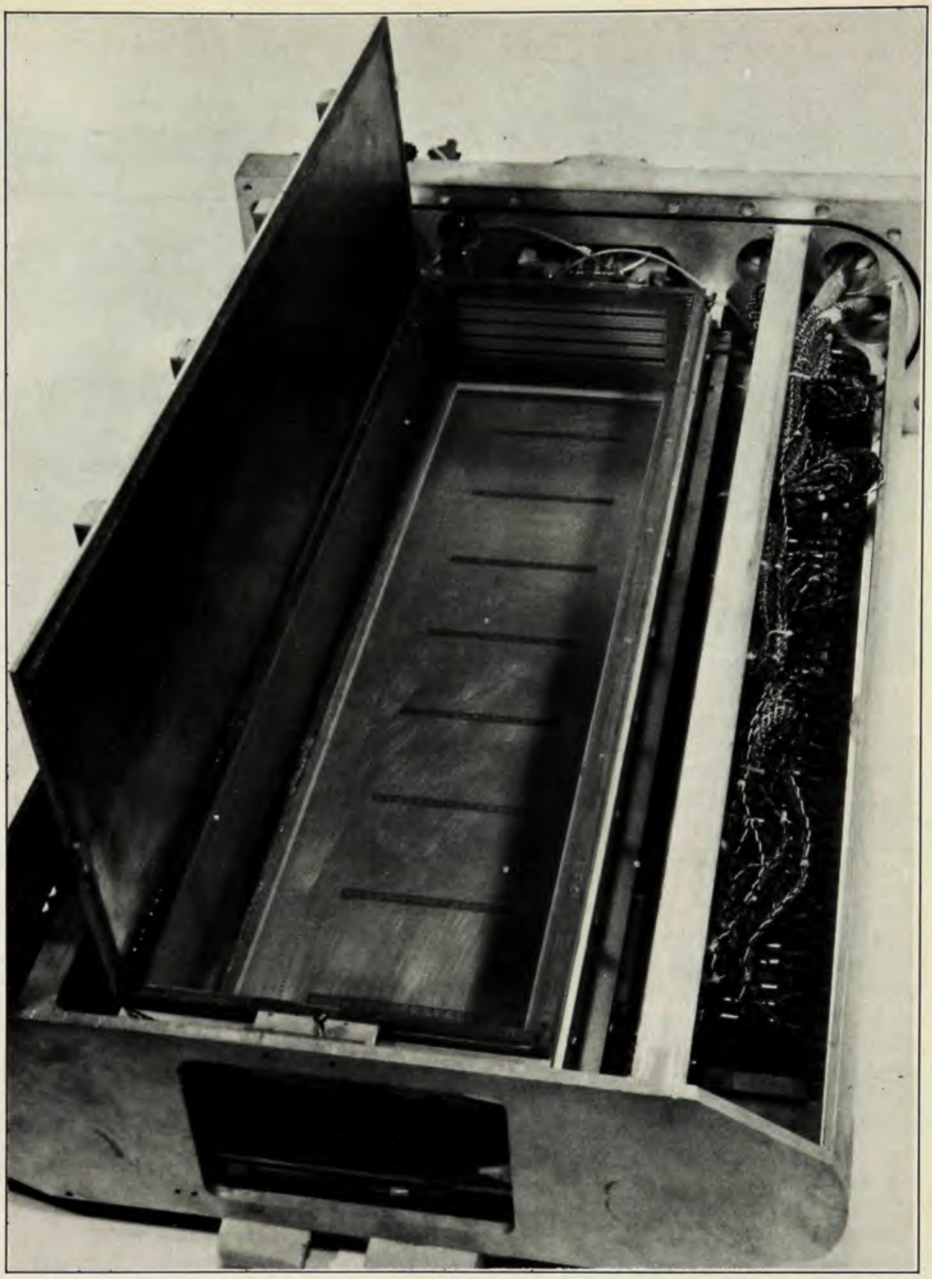
events *per hour,* at peak luminosity, is only 30. This example points out one property of paramount importance required of any PEP or PETRA detector: sensitivity over most of 4 π steradians. Every effort must be made to detect and measure all events of interest.

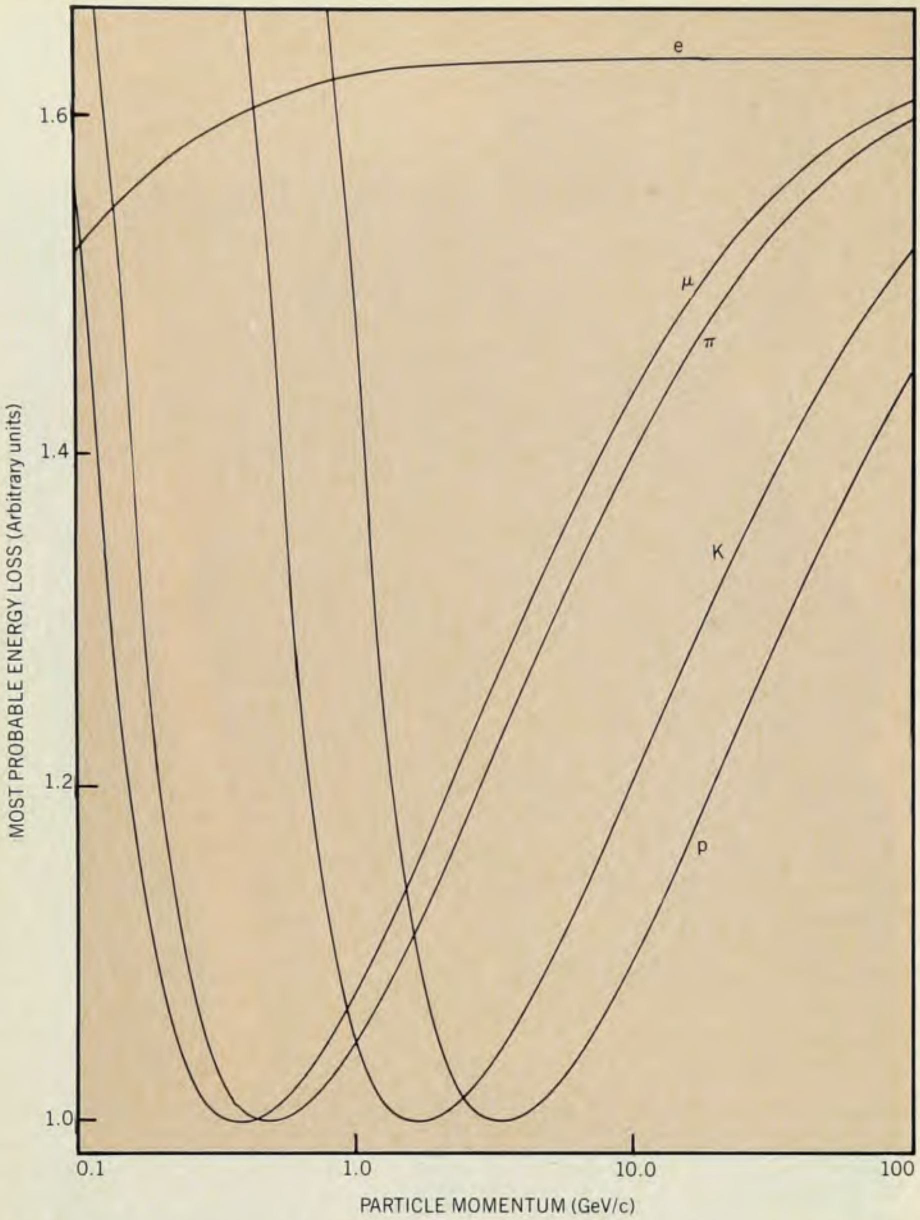
The study of muon pair production at PEP energies is of considerable interest not only as a precise test of quantum electrodynamics but also as a reaction that may display measurable effects arising from interference of the one-photon annihilation amplitude with a neutral weak current amplitude due to the existence of the proposed weak neutral boson, Z^0. These observable effects could include violations of parity and charge conjugation invariance evidenced by forward–backward asymmetry in the angular distribution with respect to the beam direction. In order to test the model dependence of the weak–electromagnetic unification theories, a statistical precision of 2% is needed.[1]



Prototype Time Projection Chamber. The photograph shows the eight rows of 8 mm × 8 mm cathode segments (pads) that provide information on particle trajectories. The 192 proportional sense wires are parallel to the pad rows. Ionization electrons left by passing particles drift perpendicular to the cathode plane under the influence of a uniform electric field. The device is immersed in a magnetic field, parallel to the drift electric field. The overall length of the active region is 76.8 cm. This prototype includes most of the projected TPC design features. Figure 1

The production of hadrons at PEP energies is also expected to provide data of major interest. In the one-photon annihilation process, hadrons are thought to be produced through pair production of a quark–antiquark state. In this poorly understood model the quark and antiquark then each materialize as a jet of hadrons that carry off the momentum and quantum numbers of the initial quarks. In this model the hadron production cross section is related to the muon pair production cross section in a particularly simple manner. Specifically, the assumption that quarks respond to the electromagnetic interaction as pointlike fermions differing only from muons in charge and mass leads to the following result at high energies. Let R be the ratio of the total cross section for hadron production to the total cross section for muon pair production. Then R is equal to the sum of the squares of the electric charges of all quark species able to contribute. As the electron–positron energy increases, new thresholds may be exceeded allowing new species of quarks to contribute, leading to a noticeable change in R. The measurement of R alone thus provides an uncommonly useful insight into the fundamental constituents of matter.[2] The careful measurement of R at PEP energies will be of high priority, but will also place severe demands on the capability of the detector to react to and measure hadronic final states of great diversity. If we extrapolate SPEAR data to PEP energies, we would expect R to fall between 5 and 10. The number of hadronic events per hour may therefore be in the range of 150 to 300.

The extrapolation of the lower-energy data also suggests that on the average about 15 particles per event will be produced, about half of these will be neutral, and that the "jet" characteristic will be a pronounced feature of the events. The axes of the jets are expected to be distributed nearly isotropically in space. The identification of particle species within the jets is of singular importance in our efforts to untangle the primary production processes from the decays of the very short-lived states leading in turn to



Most probable energy loss for various particle species in one cm of 80% argon + 20% methane at STP. Note suppressed zero. Energy loss at the minimum corresponds to 6 keV. Figure 2

the observed long-lived particles.

The tasks of detection and detailed measurement of these hadronic jet events pose the most serious challenge for the design of experiments at PEP. The ideal detector system would be able to observe events over nearly 4 steradians with very high efficiency, be able to measure accurately the momentum of at least a dozen charged particles clustered closely in space, to identify the species of each of the particles that make up the jets, to measure accurately the energies and directions of all photons emitted, and be insensitive to uninteresting backgrounds that may be many orders of magnitude more copious.

Problems of the conventional approach

In the attempt to find a conventional solution to all of these experimental problems, several factors combine to prevent an attractive design:

▶ A conventional solenoid magnetic spectrometer with a field of about 0.5 tesla would need a tracking length of about 1.5 meters for good momentum resolution. To avoid generating enormous backgrounds of synchrotron radiation, the magnetic field must be aligned parallel to the beam direction. A system of spark or drift chambers would serve to measure tracks but it provides no particle identification.

▶ If complete charged particle identification is sought over the momentum span of interest at PEP by Cerenkov and/or time-of-flight methods, then a physically enormous detector is inevitable. This is because several layers of Cerenkov detectors and very long flight paths would be required. The additional radius needed for these purposes would be about 3 meters. Because the particles must pass through the magnet coil, interactions there compromise the quality of particle identification by detectors positioned beyond it.

▶ In order to be efficient the photon detection system must rely on total absorption through shower development in a high Z material such as lead. Due to the strong scattering and attenuation of charged particles passing through the lead, the photon-detection system must necessarily lie beyond the charged-particle identification system. Thus the photon-detection system would be required to cover huge surface areas with many multi-ton multi-layer shower sampling devices.

▶ The important task of distinguishing muons from pions and other hadrons must be carried out beyond even the photon-detection system, because muons are best identified by their unique penetrating power. In practice their detection is usually carried out by absorbing all other charged particles in about one meter of steel, and labeling any emergent trajectory as a muon. Thus the outer layer of this detector approach would be a shell of steel about 10 meters in diameter, covered with track-sensitive detectors. Total weight of the detector would be about 3000 tons, dominated by the muon detector.

▶ To deal with the expected jet structure of the event, the tracking, charged-particle identification, photon and muon systems would be required to have a high degree of solid-angle segmentation so that track pile-up and resultant ambiguities might be minimized. Monte Carlo studies indicate that several hundred individual Cerenkov cells would be needed. Furthermore, low-momentum tracks, which are confined within the tracking system by the solenoid magnetic field, cause serious problems in pattern recognition.

This fictitious detector scheme would be too ponderous and expensive to survive the competitive rigors of the approval process, but it does serve to illustrate why an ambitious new approach may be welcomed if it carries the promise of the needed performance at an acceptable cost.

TPC: concept and evolution

Our discussion above suggests that if the particle-identification function could be combined within the same detector volume as the tracking and momentum-measurement functions, a very substantial reduction in overall detector size would be realized. This in turn should reduce the cost and mechanical complexity by an appreciable amount. The tracking and momentum-measurement functions ultimately depend on the processes by which charged particles lose energy in matter; so let us examine this phenomenon to see whether useful information for particle identification may be obtained. Specifically, we wish to examine the energy loss in a very thin sample of gas, for example one cm at STP, because this corresponds to a typical sensitive region of a drift or proportional wire chamber.

The most probable energy loss in an argon–methane mixture is shown as a function of momentum for a variety of interesting particles in figure 2. The family of curves actually represents a single expression that depends only on the sample thickness and composition and on the particle charge and velocity.[3] Except for the troublesome points where the curves cross, measurement of the ionization density does appear to offer a potentially useful means of distinguishing between particles with the same momentum but different velocity. It is clear from figure 2 that high-resolution measurements of momentum and ionization density are needed to minimize the regions of ambiguity found at the crossing points of the curves.

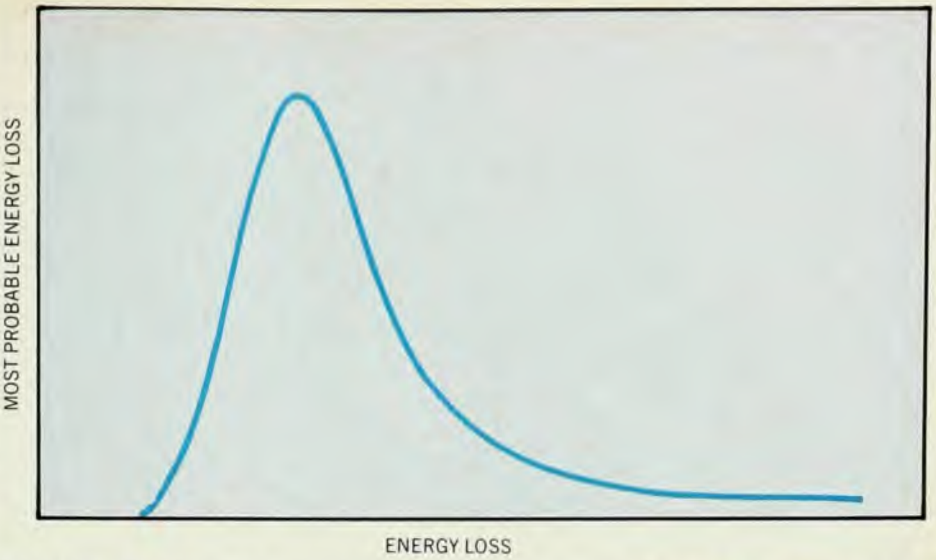
The expression represented in figure 2 is a modern version of the Bethe–Bloch formula, and for our purposes here it may be divided into three velocity regions of interest:

▸ the nonrelativistic regime, $\beta\gamma \leq 2$, where the dominant dependence of the expression is as the inverse square of β. ($\beta = v/c$, $\gamma = (1-\beta^2)^{-1/2}$, c = speed of light in vacuum.) The sensitivity here is obviously strong, and makes particle identification relatively easy.

▸ a relativistic regime, $2 \leq \beta\gamma \leq 100$ where the ionization density instead of falling passes through a minimum and then increases logarithmically with $\beta\gamma$ as a consequence of the relativistic compression of the electric field of the particle. Particles of considerable interest such as kaons and protons are expected to be produced frequently at PEP in this $\beta\gamma$ range, arguing for measurements of the ionization density with at least 3% rms resolution.

▸ An ultra-relativistic regime, $\beta\gamma \gg 100$, characterized by a gradual levelling due to increased effects of polarization of the medium by the relativistically compressed electric field. At PEP only electrons are expected to be found in this regime. The $\beta\gamma$ value for the onset of levelling out to the "Fermi plateau" depends on the density as well as the polarizability of the medium, so that only gases show an appreciable rise above the minimum around $\beta\gamma = 3.3$.

How well can one measure the most probable energy loss? Or, better, what is the optimum way to extract information about velocity from the observed energy loss? The distribution of energy losses for particles passing through 5.85 mg/cm^2 of argon–methane is shown in figure 3, as measured by a prototype time-projection chamber. The characteristic asymmetry, skewed towards high-energy losses, is a feature well known to experimental high-energy physicists, even those used to working with much thicker absorbers



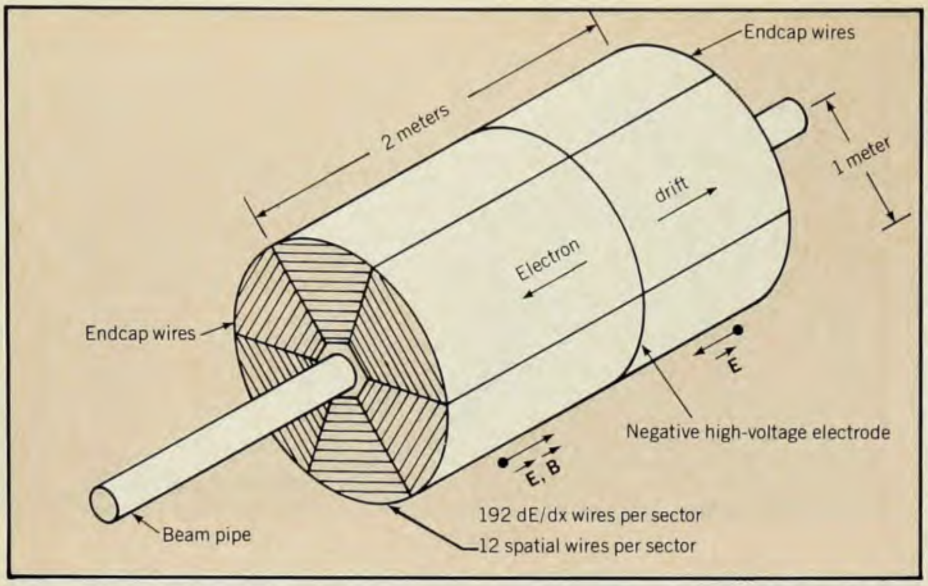
Probability distribution of the energy loss of 1.8 GeV/c pions in 4 mm of 80% argon + 20% methane at 10 atmospheres. The most probable energy loss is approximately 6.7 keV. The "Landau tail" of this distribution extends to 157 MeV, the kinematic limit for producing knock-on electrons. This distribution was obtained with a TPC prototype. Figure 3

such as plastic scintillator. This "Landau tail" is a result of the very broad $1/E^2$ spectrum of knock-on electrons produced by occasional close encounters with the atomic electrons. The strongly non-gaussian nature of this spectrum causes a very weak dependence on thickness, so that the resolution obtainable with a thick absorber is not much better than that obtainable with a very much thinner one. Conversely, the resolution obtainable with many thin absorbers can be much better than that obtained from a single absorber of equal total thickness, providing that the occasional large energy-loss fluctuations are eliminated from the data.[4] For example, suppose a particle passes through 200 individual proportional chambers and we order the resultant pulse-height ensemble according to amplitude. Take the average of, say, the lowest 100 pulse heights and compare the values after further repetitions are made with identical particles. The resolution obtained by this truncated mean method is significantly better, perhaps by a factor of three, than if we take the average of the entire ensemble of samples. Furthermore, the resolution is relatively insensitive to the fraction of samples retained over the range 30% to 70%. The prescription for the detector design is clear: provide enough gas and sample the ionization enough times so that at least 3% rms resolution is obtained.

The detailed study of this question shows that a track length of about 4 to 8 meters through a typical gas at STP is needed, and at least 100 samples should be taken. This would at first appear to cast a rather dark cloud over the whole approach, but unlike the Cerenkov or time-of-flight technique, gas is easily compressed. Beyond the direct mechanical problem of containment, though, compressing the gas by a factor of 10 to achieve a more reasonable detector size also has the undesirable consequence that the ionization density reaches its asymptotic value at a lower value of $\beta\gamma$, thereby reducing the total rise from that shown in figure 2 by about 33%. Nevertheless, the technique appears sufficiently encouraging that we now consider the question of what sort of detector geometry should be employed to obtain the sampling needed. This question, however, must be considered in parallel with the problem described earlier—how can we obtain spatial information of sufficiently high quality to reconstruct all the trajectories, even within jets.

Starting with the inevitable solenoid magnetic field parallel to the beam direction, we developed and evaluated a number of variations of the conventional instrumentation techniques. These would usually involve a huge number of drift proportional wires parallel to the magnetic field in order to measure the particle's curvature accurately and to obtain the necessary number of samples for ionization information. No convenient method was found to obtain good spatial information for the longitudinal coordinate—that is, where the track crossed along the wire. Furthermore, since the drift electric field was perpendicular to the magnetic field, $\mathbf{E} \times \mathbf{B}$ forces substantially alter the electron drift velocity and drift direction through the gas, complicating the relationship between drift time and trajectory position.

"Well, what would happen if the drift electric field direction is rotated to become parallel to the magnetic field?" This simple question posed by one of us (Nygren) when the end of the conventional road seemed inescapable, immediately led to a number of new possibilities culminating in the formulation of the time-projection chamber concept.[5]



Schematic of the Time Projection Chamber. Magnetic and drift electric fields are parallel to the cylinder axis and beam direction. Not all the readout-plane wires are shown. Figure 4

If the magnetic and electric drift fields are exactly parallel, then the absence of **E** × **B** forces invites the consideration of very long drift distances for the ionization electrons, such as a meter or more. A practical limit, however, will be set by the total voltage needed to generate the drift field over long distances. An examination of likely gases showed that argon–methane mixtures display exceptionally high electron mobilities, leading to the lowest total voltage requirement for a given drift velocity. Electron capture by electronegative molecules over a long drift interval is another possible limitation, but the most common problems, oxygen and water contamination, are easily removed from argon and methane by commercial purifiers.

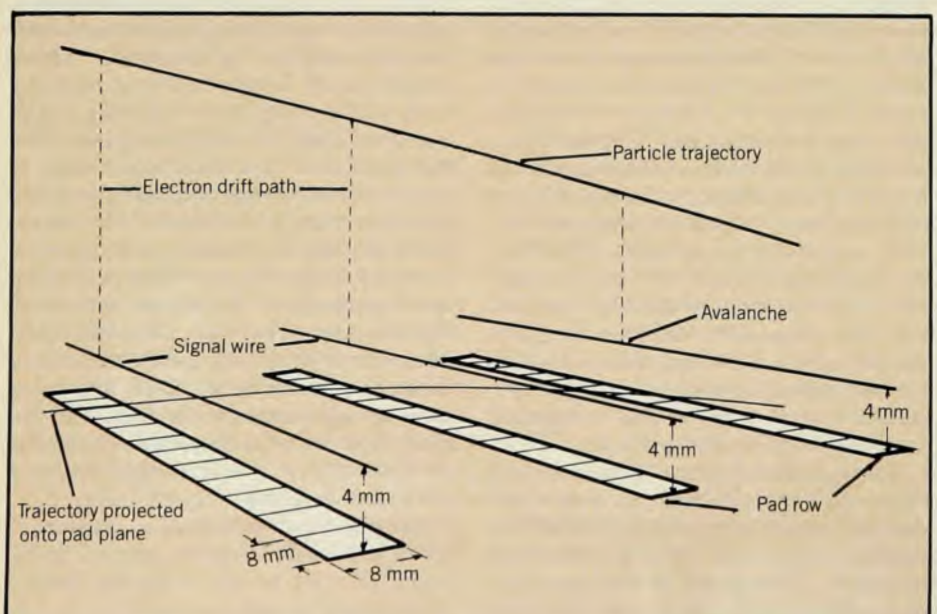
An ultimate upper limit to the drift distance will be set by the degradation of track information due to diffusion of the ionization electrons as they drift through the gas. The diffusion grows only as the square root of the drift length, and was soon recognized to be reduced substantially by the presence of a magnetic field. Known to workers in gaseous electronics for decades, this phenomenon of helical confinement was not appreciated by the high-energy physics community as a potentially useful effect.[6] The diffusion parallel to the field is unaffected by the presence of a magnetic field, but the spatial resolution requirements in this direction are quite modest.

An experimental study[7] was made of several mixtures of argon and methane to measure quantitatively the diffusion transverse to the drift field direction with and without the presence of a parallel magnetic field. The results, taken near atmospheric pressure, showed that the ratio of diffusion size with and without magnetic field could be as small as 0.1 under conditions suitable for high-energy physics. The helical confinement and high electron mobility are both providential consequences of the Ramsauer–Townsend effect in argon. This purely quantum-mechanical interference phenomenon leads to a very deep minimum in the electron–argon cross-section at energies of about ⅓ eV. In effect, the argon and, to a lesser extent, the methane, after contributing ionization, conveniently "disappear" during the drift of the ionization electrons, allowing quite a small drift field to be employed.

The diffusion data can be reliably scaled to various values of the magnetic field, pressure, and drift length. For example, the rms transverse diffusion for 1.5 tesla, 10 atmospheres, and one meter is typically slightly more than one mm for practical values of the drift field. To be competitive with drift chambers a transverse spatial resolution of 0.2 mm is needed, forcing a closer look at the information content of the track.

At 10 atmospheres, about 250 primary ionization electrons are liberated per cm of track length in argon–methane. Each electron carries information, and if a readout technique is found that weights each electron equally, then the maximum possible amount of information is obtained. The improvement factor is this example, if each electron were weighted equally and the electron origin were an ideal point source, would be $(250)^{-1/2}$ due to the gaussian nature of diffusion. In practice the proportional amplification around a wire fluctuates, due to statistical effects, and the electron source is a highly variable particle trajectory. Nevertheless, a detailed study shows that a spatial resolution better than 200 microns should be possible if a technique is used that is sensitive to all of the ionization electrons.

The practical solution here was already at hand. Georges Charpak and his colleagues at CERN had demonstrated that the positive signals induced on all electrodes near a proportional avalanche preserve most of the information of the track. These signals are the consequence of changes in the induced, or image, charges on the nearby electrodes as the positive ions generated in the avalanche move away from the sense wire. They can be sensed easily by low-noise amplifiers connected to a segmented cathode

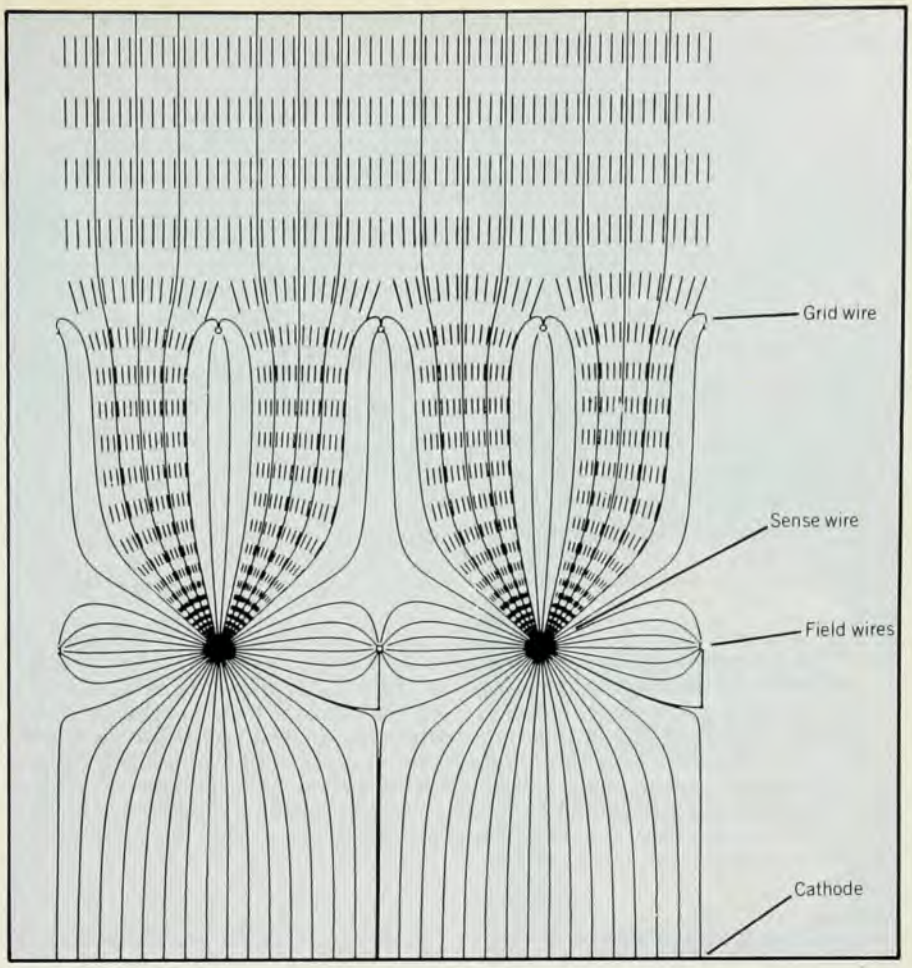


Simplified isometric representation of TPC readout plane, depicting 8 mm × 8 mm cathode segments under proportional sense wires. The center of gravity of the signals induced on the cathode segments is used to determine the positions of the proportional avalanche along the wire. Electrons drift in the opposite direction to that of the electric field. Figure 5 (see figure 5). The center-of-gravity of the induced signals provides a very high resolution estimate of where a track element falls along a proportional wire (see the article by Charpak on page 23).

The concept of the Time-Projection Chamber in the PEP environment was now nearly complete. A cylindrical volume of pressurized argon–methane would surround the beam–beam crossing point. A central conducting membrane would be connected to a large negative voltage (as much as 150 kilovolts) electrostatically dividing the cylinder into two symmetric halves. Accurately constructed voltage dividing cages around the beam pipe and outer wall would complete the drift-field generating structure. Since momentum resolution and the TPC spatial resolution both benefit from strong magnetic fields, a superconducting solenoid would be employed to superimpose a field of 1.5 tesla parallel to the drift electric field (see figure 4).

The ionization electrons generated by the passage of charged particles through the gas would be translated by the drift fields toward each end of the cylinder where a single layer of proportional wire readout planes would amplify and detect the arriving electrons. The primary tasks of the two readout planes are to sample the ionization density of all track images and to provide high-quality spatial information such that the trajectories associated with the ionization can be efficiently and accurately reconstructed.

It was immediately clear that if the cathode surfaces of the readout planes were sufficiently well segmented, then the spatial data would possess a unique three-dimensional quality, of enormous benefit to pattern recognition and reconstruction of complex events. In other words, it appeared possible to construct the cathode so that a pair of orthogonal coordinates could be obtained for a track segment in a very localized way; the third orthogonal coordinate would be obtained by measuring the drift time of the track segment relative to the beam-crossing time. Figure 5 shows a simplified view of a TPC readout plane with just three wires depicted for clarity. Track segments drift onto and are amplified by avalanches near the proportional sense wires; the cathode just behind the sense wire is locally segmented into a strip of "pads" of 0.8 cm × 0.8 cm size. The two or three pads nearest the avalanche experience induced signals that vary rapidly in amplitude with distance from the site of the avalanche. As all incident electrons contribute to these induced signals, the center of gravity of the pad's response accurately provides the avalanche coordinate along the wire, and in a way that is unaffected by the presence of other simultaneous avalanches due to tracks a few centimeters away. The pads and wires must be equipped electronically to provide high-resolution analogue information as well as the drift times associated with the analogue signals. A typical track image can be sensed by many proportional wires with locally segmented cathodes. The resultant set of three-dimensional data points define the trajectory with high accuracy and with interference only from very nearby tracks.



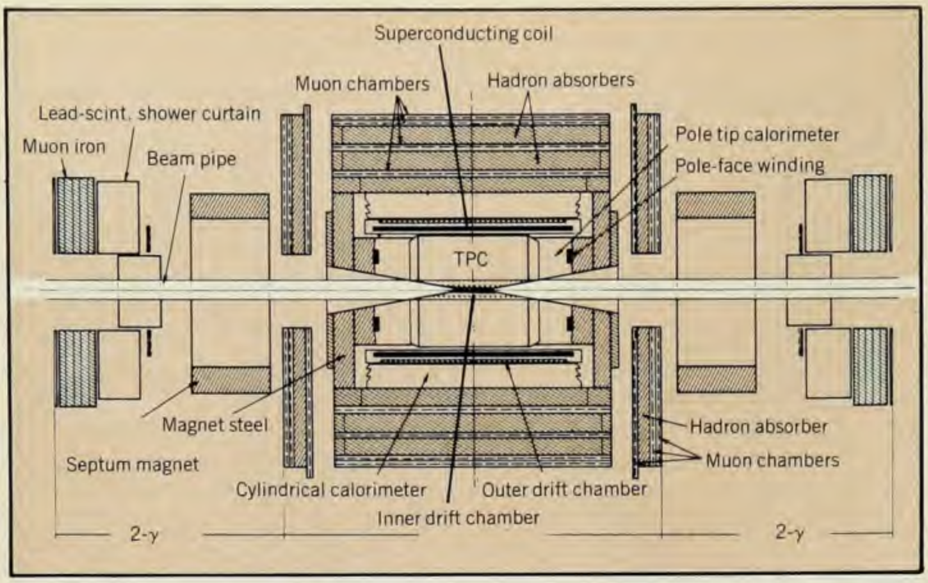
Electric field configuration in the region of the TPC endcap wedges. Sense wire voltage = 3750 volts, field wire voltage = 400 volts; grid and cathode are grounded. The dashed lines depict the paths taken by the electrons. Figure 6

For comparison, the usual practice of employing crossed-wire planes to measure projections of a particle trajectory will, for N tracks, produce N^2 possible combinations of coordinate pairs. The correct pairings can only be determined by use of additional planes at other angles, but the problem has proven to be unpleasantly difficult for high track multiplicities in the presence of strong magnetic fields. In the TPC spatial projections are essentially absent, and the only projection is in time, along the drift direction.

Each readout plane is divided into six identical and electrically independent wedge-shaped sectors. Each sector contains a set of 192 proportional wires parallel to each other and perpendicular to a radial line through the center of the wedge. The space between the wires is 4 mm. All 192 wires act to provide samples of the ionization density of tracks that drift onto them. Independent of the trajectory dip angle, any track image (trail of ionization electrons) within the sensitive volume eventually drifts completely onto this array. The cathode plane behind twelve of these wires, in equally spaced radial intervals, is locally segmented into pad rows to provide the track coordinates along the direction of these special wires.

The actual configuration of the readout plane includes a grid 4 mm in front of the sense plane and an additional array of 193 thicker "field" wires in the sense plane and spaced half-way between the sense wires. The grid serves to separate the drift region from the amplification region permitting independent control of these functions, and to capture positive ions generated by the avalanche process near the sense wire. The field wires serve to improve the electrostatic stability of the wires and to reduce the cross-talk of induced signals from neighboring sense wires on each other. The electrostatics and typical operating potentials of the actual configuration are depicted in figure 6. The amplification region has a much stronger electric field than the drift region, with the consequence that the drift-field lines are drawn through the grid to the sense wire with complete efficiency.

The positive ions generated by the av-



The PEP facility at SLAC (PEP-4), which incorporates the Time Projection Chamber. The beam–beam intersection point is at the center of the drawing. We show the Time Projection Chamber (TPC), the drift chambers, magnet coil, calorimeters (pole tip and cylindrical), iron hadron absorbers ("muon iron") and muon chambers. The TPC magnet coil and drift chambers are cylindrical when viewed end on; the cylindrical calorimeter, magnet yoke, hadron absorber and muon chambers form a surrounding hexagonal configuration. Also shown are the 2-γ (PEP-9) detectors, a pair of spectrometers with particle identification located at small angles with respect to the beams. The 2-γ detector is being constructed by a collaboration from the University of California at Davis, at Santa Barbara and at San Diego to study the interactions of pairs of virtual photons emitted from the electron–positron colliding beams at PEP. Figure 7

alanche process, although crucial for the detection of signals in the readout plane, turn out to introduce a particularly nasty space-charge effect as they enter and pass back through the drift region, migrating slowly to the central high-voltage membrane. Although the boundary surfaces of the TPC are held at well-defined potentials, the positive-ion space charge can modify the electric field substantially within the drift volume. Any radial electric field component directly distorts the track images as they drift. At PEP, the dominant source of ionization electrons in the TPC is due to machine-induced backgrounds such as synchrotron radiation. Calculations show that a narrow margin of safety should exist if the proportional-wire gain is kept as low as possible. The positive-ion space-charge problem at present is an important limitation on the applicability of the TPC technique to other areas of potential use.

The electronic complement needed to process the wire and pad signals begins with a low-noise charge-sensitive preamplifier located within a few cm of the signal source. Next, a remote amplifier shapes the signal to optimize resolving time and pulse-height resolution. The shaped signal for each pad or wire is then introduced into a charge-coupled device (or "CCD"), an analogue shift register capable of storing associated time and pulse-height information. The CCD's sample the input waveform at a rate determined by an external clock. The resultant levels are shifted along until the entire history of an event is completely stored, a time interval corresponding to the maximum drift time. As a typical electron drift velocity is six to seven cm/microsec, this interval for a one-meter drift length is about 16 microseconds. Commercially available CCD's operate in the range of 15 MHz, so that approximately 240 samples may be taken, corresponding to a sampling interval in the drift direction of 4 mm. In the absence of an event trigger the CCD clock runs continuously, spilling the uninteresting information appearing at the CCD output. The appearance of an event trigger causes the CCD clock to slow down, after the assimilation period is finished, to a rate comfortable for conventional analogue-to-digital circuitry. The slow clock rate may be as low as 20–50 KHz, corresponding to a time expansion factor of several hundred. A typical pad or wire pulse will occupy four to seven CCD samples above threshold, allowing both pulse area and drift time to be determined with good accuracy. The CCD's essentially permit the TPC to be subdivided electronically into several million relatively independent sensitive volumes, an impossibility by physical means.

TPC development program

Many of the operating principles of the TPC are being tested with a prototype, which is now operating at the Lawrence Berkeley Laboratory Bevalac in a charged-particle beam line equipped with time-of-flight and Cerenkov detectors. To fit the geometry of locally available dipole magnets, the sensitive area of the prototype is rectangular instead of wedge shaped, and the maximum drift distance is just 10 cm (see figure 1). In most other respects it resembled closely the TPC designed for PEP. The readout plane is constructed with electrostatics as shown in figure 6 with 192 active sense wires, eight of which are operating with segmented cathodes for spatial and momentum measurements.

Results obtained thus far are quite encouraging. The truncated mean energy loss for pions at 1.8 GeV/c has been measured, displaying an rms resolution of 2.7%, obtained by keeping the lowest 70% of the wire signals in the average. At this momentum, protons and pions have nearly the same most-probable energy loss (see figure 2) but due to the difference in velocity a slightly different shape in the observed energy loss spectrum exists. By using a more sophisticated statistical algorithm based on probability concepts, the data allow us to choose the correct identity 75% of the time.

The spatial resolution has been studied in the prototype by fitting tracks to a curve. Using an approximate form of the pad response function, the residuals to the fit have been found to be distributed with an rms value of 140 microns. A better understanding of the pad response and improved calibration may lower this value to near 100 microns. The work done thus far with the prototype and related electronics, including data taken with CCDs in the signal processing chain, convince us that the TPC will perform at PEP as expected.

PEP facility

The TPC is the core of a complex configuration of detectors being developed for PEP by a collaboration of about fifty physicists and an equal number of engineers and technicians from the Lawrence Berkeley Laboratory, University of California at Los Angeles, University of California at Riverside, The Johns Hopkins University and Yale University. The detector system is expected to begin data-taking operation in mid-1980. The total cost of all systems is not expected to exceed $14 million. Figure 7 schematically depicts the apparatus, which consists of five major sub-systems:

▶ The time projection chamber, which surrounds the PEP beam pipe for a length of ±1 meter and extends radially to one meter. The TPC provides pattern recognition, momentum measurement, and particle identification over more than 80% of 4π steradians. The relatively modest size of the TPC reduces the size and cost of other components at larger radii.

▶ The superconducting solenoid magnet system, which provides an exceptionally uniform field of 1.5 tesla within the sensitive volume of the TPC. Calculated non-uniformities introduce an rms transverse distortion of the track of less than 90 microns. The coil itself is approximately 2.2 meters in diameter and 3.8 meters in length and has been designed to present a minimum of material to photons passing through it (less than 0.3 radiation length for the coil itself).

▸ Cylindrical drift chambers are located at the inner and outer radius of the TPC. These chambers will be used as a part of the trigger generation and as a supplement to the TPC for the highest momentum tracks.

▸ Electromagnetic shower detectors for the measurement of photon energies and directions will be constructed with thin lead plates as the shower development medium. Argon–methane gas between the plates samples the ionization, which is then amplified by proportional wires. The magnet poletips and the entire cylindrical outer surface of the magnet coil system will be equipped with shower detectors. The shower detectors surrounding the magnet coil will be constructed as six planar modules to form a hexagonal-shaped array. The spatial resolution of these devices is expected to be ± 2 mm. The energy resolution is anticipated to be approximately 15% rms for photons of 1 GeV.

▸ The remaining subsystem is a muon identifier, which employs the traditional method of absorbing all other charged particles in a thick absorber. The muon identifier for the TPC facility is a set of steel plates with three layers of proportional wire chambers embedded within and on the outside surface. The proportional chambers are made from aluminum extrusions with a triangular cross section to provide both strength and good detection efficiency. Muons above 1 GeV/c are detected with good efficiency by this system. Interestingly, although ionization measurements will not be adequate to separate pions and muons in the relativistic range, nonrelativistic muons should be easily identified by the TPC.

In addition to the systems described above, a separate collaboration of physicists from the University of California campuses of San Diego, Santa Barbara and Davis share the same interaction region with the TPC facility, and are constructing two small-angle spectrometers, also shown in figure 7. Their apparatus is aimed at the study of non-annihilation electron–positron collisions, which are expected to display low transverse momentum characteristics. By working together, sharing data for events with particles that traverse both detector systems, the sensitive solid angle for particle detection and measurement is very close to the desired 100% of 4π steradians.

An eye to the future

In this article we have discussed not only the principles of the TPC, but have also attempted to present some aspects of how the concept evolved. In fact, the evolution of the TPC ideas followed a somewhat more tortuous path than could be presented in this article, and has also benefited from suggestions and contributions made by many people.

New developments may lead to additional applications of the TPC, such as the study of heavy-ion collisions or in proton–antiproton colliding-beam experiments. Due to the very high background levels of ionizing particles expected for the proton–antiproton situation, the TPC would be feasible only if the technique could be made less vulnerable to the distortions of the drift electric field caused by positive-ion feedback. An improvement here of several orders of magnitude appears possible if the grid could be transformed into an electron gate, allowing ionization electrons to enter only when an interesting event has occurred. Because the positive ions move slowly, even the positive ions generated by the interesting event would be prevented from returning to the drift region by closing the gate soon after the electrons have entered the amplification region. If this could be achieved, the net positive-ion feedback would be reduced to essentially zero.

Other beneficial developments may arise in the area of high-speed analogue and digital signal-processing electronics. Here, in particular, it may be risky to speculate on the future, but as the reader may have concluded by now, we are not afraid to make projections in time.

References

1. Detailed discussion of the experimental capabilities needed to confront the predictions of the various models attempting to unify weak and electromagnetic interactions are given in the 1975 PEP Summer Study, LBL-4800, 1975.
2. S. D. Drell, PHYSICS TODAY, June 1978, page 23.
3. H. D. Bethe, Ann. Physik **5**, 325 (1930), F. Block, Z. Physik **81**, 363 (1933), L. D. Landau, J. Phys. USSR, **8**, 201 (1944), R. Sternheimer, R. F. Peierls, Phys. Rev. B. **11**, 3681 (1971).
4. A. I. Alikhanov, V. A. Lubimov, G. P. Eliseiev, *Proceedings* of CERN Symposium on Particle Accelerators and Pion Physics, 1956, pages 87–98.
5. D. R. Nygren, "Proposal to Investigate the Feasibility of a Novel Concept in Particle Detection," LBL internal report, February 1974.
6. J. Townsend, *Electrons in Gases,* Hutchinson's Scientific and Technical Publications, London (1947), R. W. Crompton, L. G. H. Huxley, *The Diffusion and Drift of Electrons in Gases,* Wiley, New York (1974).
7. "Proposal for a PEP Facility based on the Time Projection Chamber," PEP Proposal #4, Johns Hopkins University, Lawrence Berkeley Laboratory, University of California at Los Angeles, University of California at Riverside, Yale University, 1976. This document contains detailed discussions of many of the ideas discussed in this article. Diffusion in the presence of magnetic fields is discussed in Appendix A6. ☐