Time-projection chambers

A gas in parallel electric and magnetic fields makes an elegant detector able to identify particles over a broad momentum range and to measure their tracks in three dimensions.

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Since its invention only ten years ago, the time-projection chamber has proven so useful as a particle detector that some are calling it the "bubble chamber" of the 1980s and 1990s. The enormous appeal of this new detector stems from its ability not only to reconstruct the trajectories of charged particles in three dimensions, but also to identify particles by measuring the ionization energy that they deposit along their tracks. The time-projection chamber can make these measurements over a large solid angle and in very crowded environments where many tracks are created at the same time.

From versions the size of a grapefruit for constructing decay vertices, to versions weighing ten thousand tons or more to detect proton decay, the time projection chamber in its current and proposed uses shows a surprisingly large range of application. In Europe two of the largest detector projects ever, DELPHI and ALEPH, will use time projection chambers as their main detectors. Similarly, the TOPAZ detector being built in Japan for the new TRISTAN electron–positron collider has a time-projection chamber at its core. These large detectors for electron–positron colliders follow in the footsteps of the PEP-4 time-projection chamber at Stanford, currently the most comprehensive detector taking data at the electron–positron collider there. Specialized time-projection chambers have been built and operated successfully: the recoil spectrometer built at Fermilab by physicists from Rockefeller University to study high-energy diffraction dissociation, the detector built at TRIUMF in Canada to look for violation of lepton number conservation in muon capture, and a detector built at Los Alamos to measure with unprecedented accuracy the positron spectrum from muon decay. New applications of time-projection chambers are under development: Physicists at Irvine have built a time-projection chamber to study neutrinoless double beta decay, and efforts are under way to develop liquid-argon time-projection chambers for massive experiments to study nucleon decay. At the other end of the spectrum, particle physicists are studying very small time-projection chambers for vertex detectors to observe and tag short-lived particles produced very near primary collisions.

A typical time-projection chamber consists of a large volume of gas in uniform and parallel electric and magnetic fields. Because of the magnetic field, charged particles follow curved trajectories in the gas. They ionize the gas along these trajectories, depositing an amount of energy that depends on their charge and velocity. In the low-velocity or nonrelativistic regime, where $\beta\gamma$, or $(v/c)\,(1-v^2/c^2)^{-1/2}$, does not exceed 2, the ionization energy loss is proportional to $1/\beta^2$. In the relativistic regime, where $\beta\gamma$ is between 2 and 100, the ionization reaches a minimum and then begins to rise logarithimically with $\beta\gamma$ as a consequence of the relativistic compression of the electric field of the particles. In the ultrarelativistic regime, where $\beta\gamma$ exceeds 100, the ionization energy loss gradually levels off due to the polarization of the medium by the compressed electric field.

The electrons liberated by the ionization process drift under the influence of the electric field toward one end of the detector. Their arrival time at the detector end of the chamber (a typical detector end is shown in figure 1), together with the known drift velocity,

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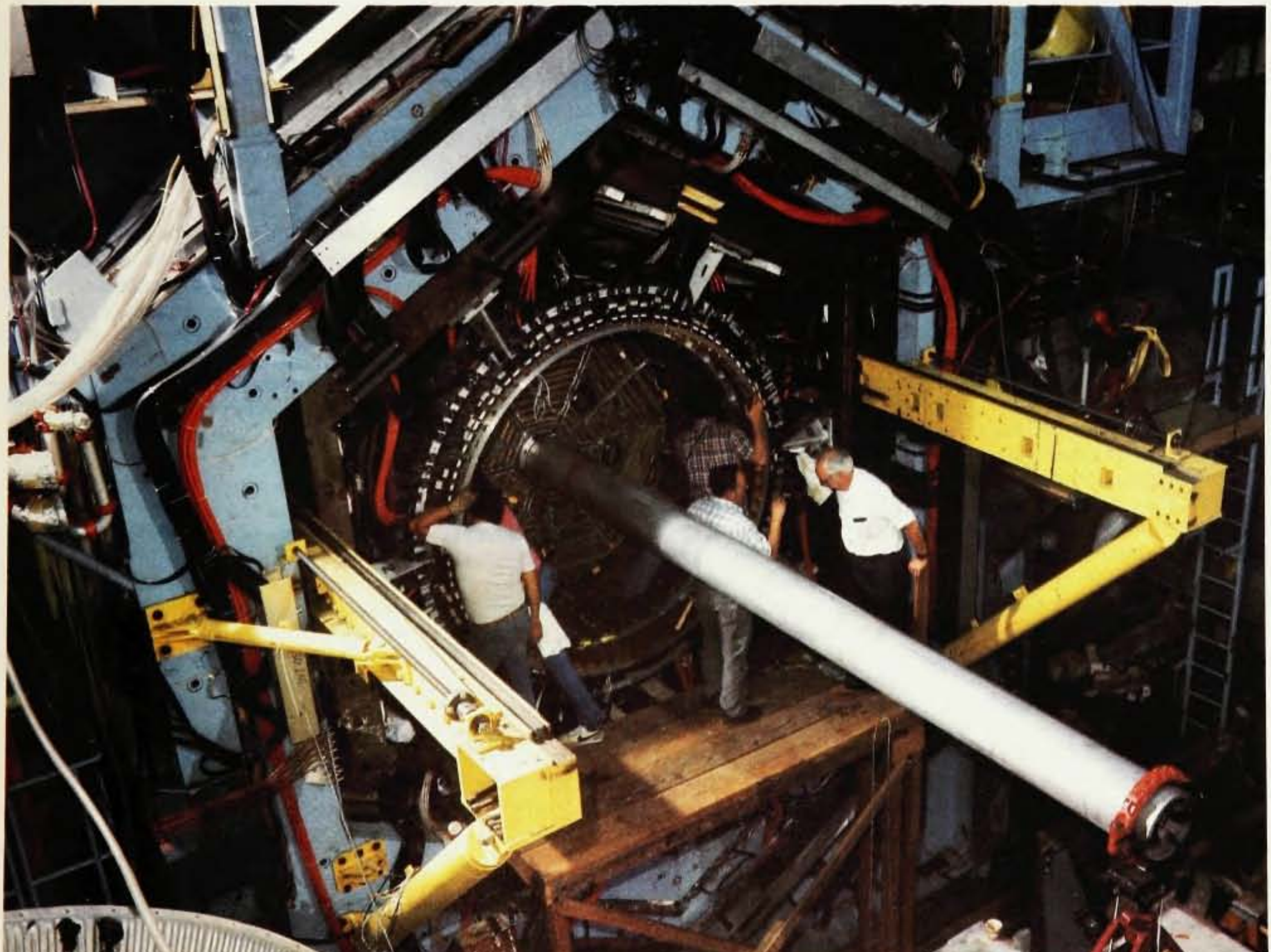
Time projection chamber being installed in the magnet at the PEP-4 facility at the Stanford Linear Accelerator Center. At left is a front view of one of the detector sectors that make up the ends of the cylindrical chamber. The sector has 183 sense wires, which run horizontally in this photograph, and 15 strips of square sense pads. The backs of six detector sectors are visible in the photograph below. Figure 1



yields the spatial coordinate of the track in the drift direction, while the point of impact on the detector end yields the other two orthogonal coordinates. In addition, the amount of ionization that arrives at the detector end yields the amount of ionization that the particle deposited along its trajectory. The momentum, measured by the curvature, and the velocity, measured by the ionization, together identify the type of particle that produced the track.

In this article we follow the development of time-projection chambers from their invention by David Nygren of Lawrence Berkeley Laboratory in 1974 to the present research and development efforts aimed at extending their use to new areas.

Origin of the concept

The years 1973 through 1975 saw a great deal of study and debate at Lawrence Berkeley Laboratory, the Stanford Linear Accelerator Center and elsewhere on the merits of different technologies for the new generation of detectors to be built for the "positron–electron project," or PEP collider, which the two laboratories were proposing to build.[1] It was expected then that the collisions at PEP would produce pairs of highly collimated particle jets, each with some seven to eight charged particles and about an equal number of photons. The ideal detector would not only measure the momentum of all the charged particles and the energies of all the photons, but would also identify all final-state charged particles—electrons, muons, pions, kaons and protons. The traditional detectors would have measured the trajectories of charged particles with proportional or drift chambers, which are arrays of wires that collect and amplify the ionization left behind by the particles. Proportional chambers are so named because the signal out of the wires is proportional to the amount of ionization created by the particles. These traditional detectors would have identified particles using large arrays of Cherenkov counters, all inside magnetic fields would in turn be surrounded by photon and muon detectors. This approach led to designs that were thought to be impractical or exceedingly costly. In the discussions of new detectors, it seemed inevitable that no single device could be built with all the desired characteristics.

Nygren's concept of the time projection chamber emerged from these discussions as a leap in particle detector technology that might, after all, allow the development of a nearly ideal detector.[2] The concept had its roots in earlier work by Georges Charpak, Wade Allison and others who developed drift chambers with long drifts and schemes to measure position by signals induced in cathode strips; they were also proposing to identify particles by the repeated sampling of the particles' energy loss in drift chambers. The concept of the time-projection chamber was a synthesis of many ideas from many fields.

The time-projection chamber is the first detector to exploit the fact that parallel electric and magnetic fields suppress diffusion. Figure 2 shows the position of a time-projection chamber in a colliding-beam experiment. Particles from the primary collision create tracks of ionization that eminate from a vertex in the center of the detector. The tracks are clusters of ionization in the gas, and the electrons in these clusters drift towards the ends of the detector under the influence of a highly uniform electric field. The drifting electron clusters tend to broaden in space due to diffusion, but the magnetic field suppresses this broadening by causing the electrons to follow magnetic field lines as they drift. In a time-projection chamber operating at atmospheric pressure, the magnetic field suppresses this transverse diffusion by as much as a factor of ten, permitting long drifts without significant loss of information on the trajectories of the particles.

The basic detector is thus extraordinarily simple: a suitable gas in uniform parallel electric and magnetic fields. All the complications are removed to the ends of the detector, where one must measure the arriving clusters of ionization. To measure these clusters the detector uses multiwire proportional chambers operating at unusually low gain. The design of the low-noise electronics necessary to operate at low gain came from nuclear spectroscopy. The purpose of the low gain is to keep the avalanches at the wires relatively small so that they do not distort the ionization information that identifies the particles. The avalanches produced as the ionization arrives at the detecting anode wires induce signals in the wires and in the adjacent cathode. If the cathode is segmented into pads, then the signals detected at the pads determine the position of the avalanche along the wire. These pads are visible in the photograph of the sector in figure 1, and are represented by the squares in figure 2. Thus the anode and cathode signals provide two coordinates in the plane perpendicular to the drift, and the travel time of the clusters multipled by the known drift velocity gives the third spatial coordinate. The novel use of drift time to complete the three-dimensional information led to the coining of the name "time-projection chamber."

Because the ionization deposited along the particle trajectory is measured many times along the track, it is possible to use the histogram of ionization samples to identify the type of particle produced. The histogram of ionization samples is characteristic of the particle velocity. Because the detector is in a magnetic field, measurement of the spatial coordinates determines the curvature of the track and hence the momentum of the particle. By measuring both velocity and momentum, the time-projection chamber can identify particles over a broad momentum range.

The massive amount of information available from the time-projection chamber requires the application of electronic techniques previously unknown for particle detectors. The original time-projection chamber stored pulse information from wires and pads in analog form in linear charge-coupled devices, with one CCD per detecting element (wire or pad).

The above ideas were tested in a small prototype at the Lawrence Berkeley Laboratory Bevatron and formed the basis of the PEP-4 detector, the most ambitious time-projection chamber project undertaken to date.

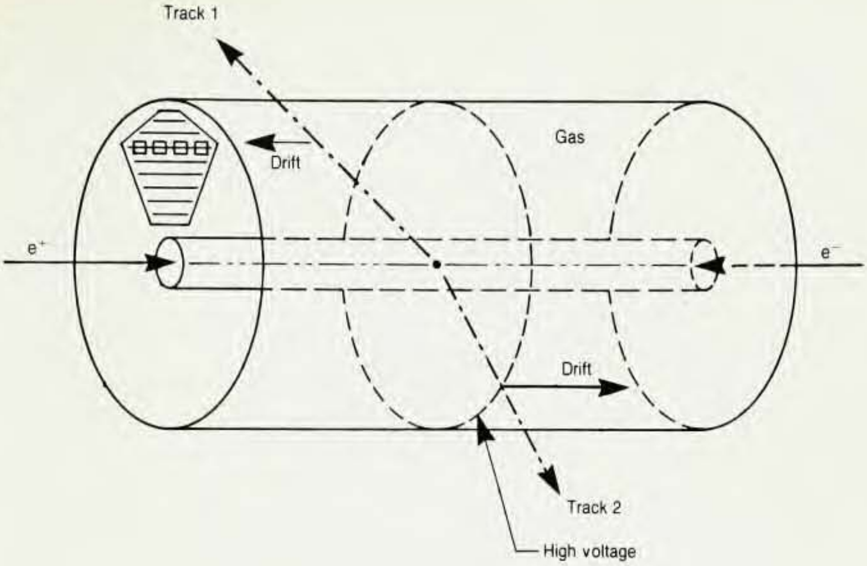
The first time-projection chamber

The PEP-4 facility is a large detector complex[3] used to measure and identify the particles resulting from collisions of electrons and positrons with a center-of-mass energy of 29 GeV at the Stanford Linear Accelerator Center e^+e^- storage ring PEP. It was built by a collaboration of about seventy physicists and an equal number of engineers and technicians from Lawrence Berkeley Laboratory, the University of California at Los Angeles, the University of California at Riverside, Johns Hopkins University, the University of Massachusetts, the University of Tokyo and Yale University.

Figure 3 schematically depicts the PEP-4 facility, which consists of the following major subsystems:[4]

▶ The time-projection chamber[5] itself—a cylindrical drift volume two meters long and two meters in diameter, filled with a gas mixture of 80% argon and 20% methane at 8.5 atmospheres pressure. The cylinder surrounds the vacuum pipe in which the high-energy particle beams move and interact. A central membrane at -75 kV and a series of equipotential rings at the inner and outer radii of the cylinder produce the axial electric field in the chamber. Each endcap contains six proportional chamber modules to detect the drifted ionization. Each of the six sectors contains 183 sense wires, having a radial spacing of 4 mm. Fifteen of the sense wires in each sector have the cathode plane locally segmented into a strip of square pads, 7.5

Detection volume. This schematic diagram of the heart of a time projection chamber shows two trails of ionization left by particles. Electrons in the trails drift along axial electric and magnetic fields and are detected at the endcaps. Figure 2



mm on a side and located 4 mm under the wire, as shown in figure 1.

▶ A conventional magnet, providing a uniform solenoidal field of 4 kG. A thin superconducting coil only 0.9 radiation lengths thick will soon replace the conventional magnet and produce a 14 kG field. This increase in magnetic field will improve the momentum resolution of the time-projection chamber by a factor of almost four.

▶ Cylindrical drift chambers at the inner and outer radii of the time-projection chamber, used primarily to provide a fast pretrigger for the entire detector. The inner chamber of four layers imposes strong spatial and temporal restrictions on track candidates, limiting cosmic-ray and synchrotron radiation backgrounds. The outer chamber of three layers signals the presence of tracks at large angles or tracks from particles with high transverse momentum, thus reducing background from two-photon processes and beam–gas interactions.

▶ Electromagnetic calorimeters, both surrounding the magnet coil and closing the ends of the coil, to provide nearly complete coverage for the detection of photons and electrons. In these detectors, the photons and electrons create electromagnetic "showers"—cascades that involve successive generations of electrons, positrons and photons that propagate until all energy is absorbed. These calorimeters consist of multiple layers of lead (in which the showering occurs) interspersed with detecting chambers that measure the spatial coordinates and the energy liberated in the showers.

▶ A muon detection system, which identifies muons by absorbing all other charged particles in thick iron absorbers. This system includes four layers of proportional chambers interspersed with layers of iron whose total thickness is one meter. The proportional chambers are made from aluminum extrusions with a triangular cross section to provide both strength and good detection efficiency.

At each end of the PEP-4 facility are small-angle spectrometers to study the two-photon interaction, namely, the collision of two photons that are emitted in some electron–positron collisions. These detectors, known as PEP-9, were built by a collaboration of physicists from the Davis, San Diego and Santa Barbara campuses of the University of California, the University of California Institute for Research at Particle Accelerators, and the Nationaal Instituut voor Kernfysica en Hoge Energie Fysica NIKHEF, in Amsterdam.[6] The PEP-4 and PEP-9 detectors together cover most of the solid angle for particle detection and measurement, and members of the two collaborations are working together in the study of the two-photon processes.

In the PEP-4 time-projection chamber, amplification of the primary ionization at the sense wire induces signals on the nearest two or three segmented cathode pads under the wire. A linear charge-coupled device records the pulse heights of the signals on the wires and pads every 100 nsec. The spatial resolution of the time projection chamber is 160 microns in the radial direction and 350 microns in the axial direction. The momentum resolution dp/p that we obtain using a 4 kG magnetic field is given by $(dp/p)^2 = (0.06)^2 + (0.035p)^2$, with p in GeV/c; 4% is a typical value.

The time-projection chamber identifies a particle by simultaneously measuring its momentum and dE/dx, the rate at which it loses energy to ionization over distance. The pulse heights of the signals on the sense wires in each sector provide up to 183 data points on the ionization energy loss. We correct the pulse heights for track length, wire gain, electronic gain and electron capture along the drift path. Because the ionization energy loss has a broad spectrum with a long high-energy tail, one needs many samples to determine accurately the ionization energy loss dE/dx. We define dE/dx for each track as the mean of the smallest 65% of the individual samples.

Taking data

Figure 4 shows a typical multihadron event in positron–electron annihilation, as recorded by the PEP-4 detector. The measurements of ionization energy loss identify unambiguously all but one of the particles.

Figure 5 shows the distribution of ionization energy loss dE/dx plotted against momentum measured in the PEP-4 time projection chamber for tracks in multihadron events from electron–positron anihilation. The figure also shows the dependence predicted by theory for various particle types. In the region of low momentum, the pion, kaon and proton bands are well separated. When the momentum is close to and above that which creates the minimum amount of ionization (the lowest points on the curves in figure 5), a maximum-likelihood statistical method separates the various particle types.

Within a year of taking its first block of data with the PEP-4 detector, members of the collaboration have published or submitted for publication results on the following physics topics:[7]

▶ The search for fractionally charged particles. The time-projection chamber has made it possible to improve the previously established limits on the production of quarks or diquarks of charge $\frac{1}{3}$, $\frac{2}{3}$ and $\frac{4}{3}$.

▶ The production cross sections and multiplicities of pions, kaons and protons produced in electron–positron annihilation. These data contribute to understanding the process by which quarks and gluons fragment and form hadrons.

▶ The study of prompt electrons to identify charm- and bottom-quark events, the charm and bottom quark semielectronic branching fractions, the shape of the bottom quark fragmentation function, and the charm and bottom quark forward–backward asymmetry.

▶ The production of phi mesons. The yield of these particles is closely related to the quantum number, energy flow and hadronization of the original partons in electron–positron annihilation.

▶ Proton production. Because the momentum of protons is only slightly degraded in the decay of resonance particles, their production reflects the distribution of primary fragmentation products in electron–positron annihilation.

In all of this research, the time projection chamber identified particles by measuring their rate of energy loss through ionization, dE/dx. The search for fractionally charged particles is a good example. The time-projection chamber is well suited to look for stable particles with charges $\frac{1}{3}$, $\frac{2}{3}$ or $\frac{4}{3}$, because the ionization energy loss dE/dx is proportional to the square of a particle's charge. One looks for fractionally charged particles of mass 1 to 10 GeV/c^2 in regions not populated by stable particles of unit charge. The top and bottom right corners in figure 5 represent this region. Results from the PEP-4 time-projection chamber have lowered our upper limit on the production of fractionally charged free quarks by a factor of ten.

Overcoming problems. The PEP-4 time-projection chamber, being the first of its kind, was not without its share of problems. The most significant was due to nonuniformities in the electrostatic drift field, which gave rise to track distortions that degraded the momentum resolution. These nonuniformities had two sources: a space charge in the drift region and error in the potentials on the structures that shape the drift field.

The space charge was made up of positive ions left behind by avalanches of electrons at the sense wires. Such a build-up of positive ions in a time projection chamber's drift region seriously limits its operation at high event rates or in high-background environments. Adding an additional grid to the endcap sectors solves[8] the problem. The grid serves as an electronic shutter. It is kept closed, thus preventing ionization electrons from reaching the sense wires, until it receives a signal to open. It stays open only for the time it takes the drifting electrons to reach the sense wire. During this sensitive period the time-projection chamber records the data as it normally does. These shutters, which are called gated grids, have been installed on all twelve of the PEP-4 sectors, and should reduce the positive-ion space charge by a factor of 1000.

The electric drift field in the PEP-4 time-projection chamber is shaped by conductive rings spaced every 5 mm in an insulating support. A series of precision resistors determines the potentials of the rings. It took considerable effort[9] to discover that zones of anomalous conductivity in the supporting substrate, a Nema G-10 fiberglass–epoxy laminate, were the source of nonuniformities in the electric field. Coating the substrate surface with a slightly conductive layer of polyurethane solves this problem. The resistance of the coating is much lower than that of the substrate, but much higher than that of the resistors that establish the potential on the rings. The coating uniformly grades the potential between the rings and shields the drift region from the nonuniform potentials inside the fiberglass laminate substrate. All of the field-shaping structures in the PEP-4 detector are now coated with this polyurethane coating. This modification, along with the gated grids, promises to reduce the electrostatic distortions of the time-projection chamber to below the level of the intrinsic spatial resolution of the device.

Other time-projection chambers

At the same time that the PEP-4 detector was being built, physicists were developing other time-projection chambers for experiments with simpler requirements.

At TRIUMF in British Columbia, Doug Bryman of the University of Victoria and Cliff Hargrove of the National Research Council of Canada have overseen the building of a time-projection chamber. They intend to use it primarily for an experiment to search for the lepton-number-violating nuclear muon-capture reaction $\mu^- + Z^A \rightarrow e^- + Z^A$ with a sensitivity nearly 10^{12} times that needed to detect ordinary muon capture.

The TRIUMF time-projection chamber[10] has two hexagonal endplates, one meter across, with a central hole and six cutouts for the proportional chamber modules, or sectors. The end plates are 69 cm apart, and are mounted on a central tube 30 cm in diameter. Each sector consists of an aluminum plate, which acts as a ground plane and provides mechanical support, attached to a printed circuit board that supports the segmented cathode pads. The aluminum plate has channels cut out for twelve sense wires. The chamber is in a 10-kG magnetic field having a uniformity of better than 0.3%, and is filled with 80% argon and 20% methane at one atmosphere.

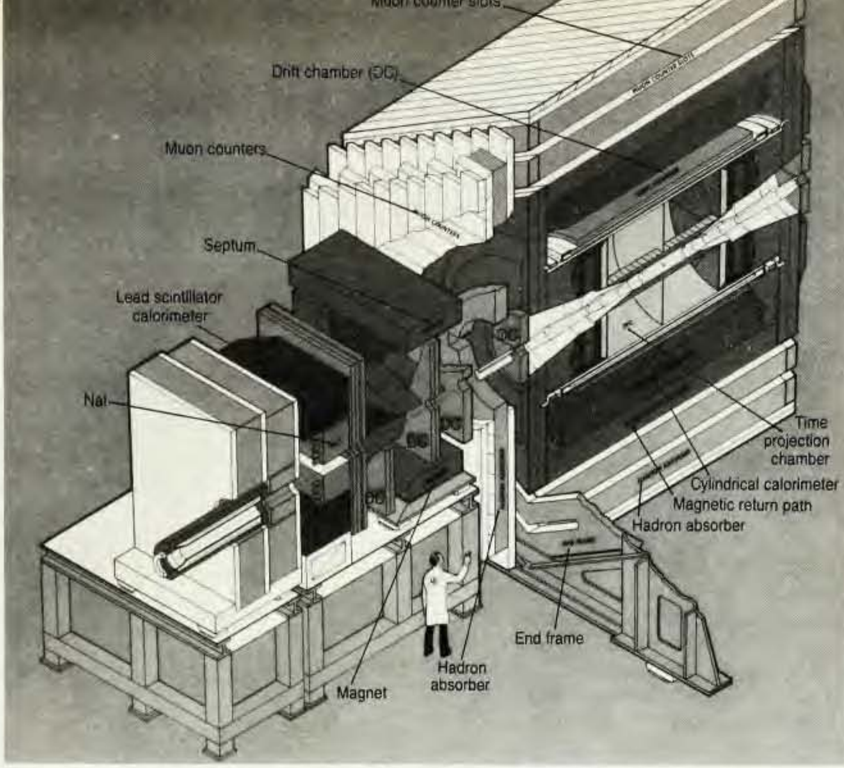
Extensive studies of the spatial resolution of the TRIUMF time-projection chamber show its best resolution to be about 200 microns. This is attained with the minimum drift length and the optimum angle between the particle track and the sense wires. Because the electric and magnetic fields are no longer parallel near the sense wires, $\mathbf{E} \times \mathbf{B}$ becomes nonzero, and the resolution deteriorates rapidly at angles larger or smaller than the optimum one.

The TRIUMF time-projection chamber has already produced some results. It recorded the first measurement[11] of pion double-charge exchange at low energy, which is a sensitive indicator of the correlations between nucleons.

A group at Rockefeller University in New York led by Konstantin Goulianos has developed another time-projection chamber, this one to serve as part of a spectrometer for recoiling protons in an experiment at Fermilab investigating the diffraction dissociation of 20–170 GeV photons on hydrogen. In the diffraction process, a photon grazes a proton, yielding hadrons and a recoiling proton: $\gamma + p \rightarrow X + p_{recoil}$; here X represents the hadrons from the diffraction dissociation of the photon. One way to analyze this interaction is to think of the photon as a superposition of hadronic states, such as mesons, that scatters off of the proton and then dissociates into its component hadrons; this is called diffraction dissociation. To see narrow resonances in the dissociation cross section, one needs good mass resolution on the recoil proton. This calls for good angular resolution, which for low-energy recoils requires the use of a gas target. The material along the path of the protons inside the recoil detector must also be kept small. Event-rate considerations dictate the use of a high-pressure target and a detector that covers a large solid angle. The Rockefeller group has satisfied these requirements by using a 15-atmosphere hydrogen time-projection chamber both as the target and as the detector of recoil protons.

The Rockefeller detector[12] consists of two cylindrical drift regions arranged in tandem, each 45 cm in diameter and 75 cm long. Instead of individual proportional chamber modules at the endcaps as in the PEP-4 and TRIUMF time-projection chambers, this one has on each end a set of concentric octagonal sense wires that record the arrival time and amount of ionization from the recoil particle. A computer translates

Central PEP-4 facility and forward PEP-9 facility. This cutaway diagram shows the time projection chamber and the instrumentation that surrounds it. At the front are the small-angle spectrometers known as PEP-9. Figure 3



the time differences between sense wires into polar angles, and pulse heights into the ionization energy loss dE/dx. Plastic scintillation counters inside the high-pressure vessel stop the particles and determine their energies. Comparing the rate of energy loss with the energy identifies recoil protons.

Preliminary results[13] from the Rockefeller diffraction dissociation experiment show that the differential cross section is consistent with what is predicted by some of the existing models.

A group from Los Alamos National Laboratory, the University of Chicago and the National Research Council of Canada has developed a time-projection chamber for a very-high-statistics measurement of the positron spectrum from normal muon decay. By measuring the direction and momentum of the decay positron with high precision, this experiment at LAMPF should improve upon the limits of the weak-interaction coupling constants by a factor of five. The time-projection chamber has features that are particularly advantageous to this experiment in that it allows high-precision measurement of kinematic variables of the positron over most of the dynamic range of muon decay. In addition, because the gas in the time-projection chamber stops muons, systematic errors arising from multiple scattering, bremsstrahlung energy loss, annihilation in flight, and unseen decay vertices are greatly reduced.

The LAMPF time-projection chamber[14] consists of a cylindrical drift region 122 cm in diameter and 52 cm long. The readout plane on the end of the cylinder contains 21 identical square proportional-chamber modules. Each module has 15 sense wires, with 17 segmented cathode pads under each wire. Analog-to-digital converters receive the pulse height signals from the pads and store them every 40 ns. The LAMPF time-projection chamber has passed tests with cosmic rays, laser-induced tracks and a small number of muon decays.

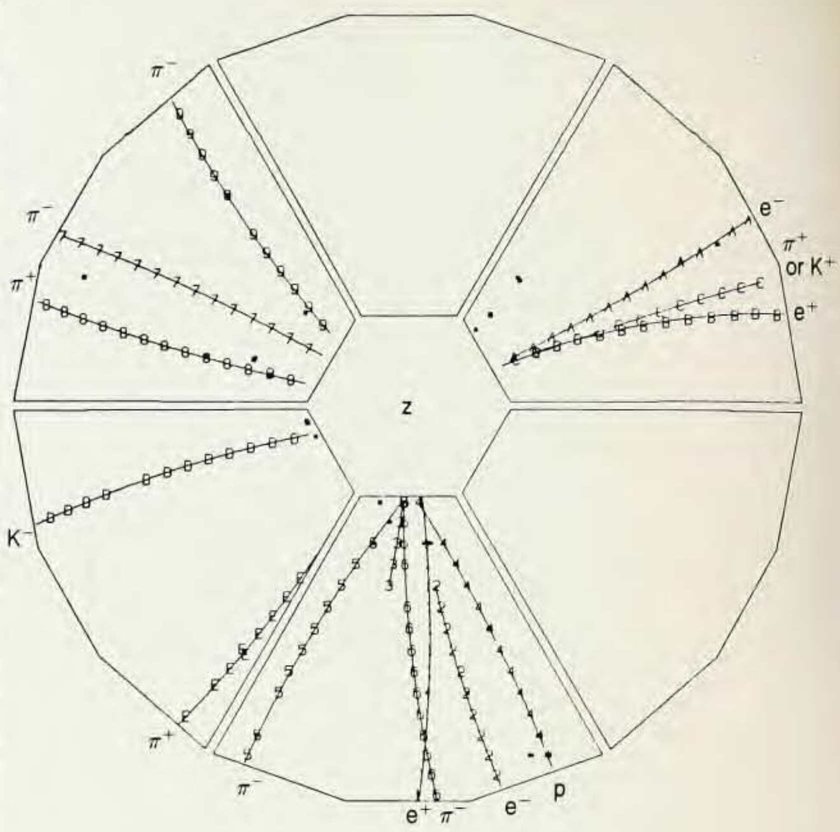
Second-generation chambers

The time-projection chamber was originally developed to solve problems associated with the design of detectors for the PEP collider, so it is not surprising to find the concept being applied extensively at the new electron–positron colliders. Two massive new electron–positron collider rings are under construction. The first one, TRISTAN, is a project of the KEK accelerator laboratory in Japan and is scheduled to be operational in 1987. It will have a maximum energy of about 70 GeV in the center-of-mass reference frame. The second one, the LEP collider ring at CERN in Geneva, is scheduled to be operational in 1989. Its initial maximum energy will be about 100 GeV in the center-of-mass frame, and this will eventually grow to 190 GeV. The size of an electron–positron collider ring is proportional to the square of the energy. Thus, these new rings are very large undertakings that make colliders of the present generation, such as PEP and PETRA, look like small prototypes.

At the TRISTAN collider, a time projection chamber is under construction. The project, TOPAZ,[15] is a collaboration between KEK, the University of Tokyo and several other Japanese universities. This detector will operate at 4 atmospheres pressure in its own pressure vessel, and will be surrounded by a 10-kG superconducting magnet. A lead–glass photon calorimeter and a multilayer muon detector will operate outside the magnet. The TOPAZ time projection chamber is very similar to the PEP-4 detector, which is not surprising, because the University of Tokyo group is one of the collaborating institutions in the PEP-4 detector. The TOPAZ machine features improved field cages and insulators, an improved electronic readout system, a gated grid for suppression of positive ions, and "serrated" pad boundaries to optimize position resolution by the pads. Figure 6 is a sketch of the TOPAZ time-projection chamber.

At the LEP collider, two time projection chambers—DELPHI and ALEPH—have been approved for construction. While both are to operate at atmospheric pressure, their goals and implementation are different.

The DELPHI project[16] is a collaboration of over 200 scientists from 29 institutions in 12 countries, under the leadership of Ugo Amaldi from CERN. At the core of the detector is a relatively small time-projection chamber used primarily for three-dimensional pattern recognition and the identification of low-energy electrons. The chamber occupies an effective radial space of only 75 cm, about the same as the PEP-4 time-projection chamber. Neither the tracking nor the particle identification provided by such a small chamber operating at atmospheric pressure are completely adequate for the large energies at LEP, which at the lowest end are three times greater than the energies a



at PEP. The DELPHI time-projection chamber is therefore supplemented by drift chambers and "ring imaging" Cherenkov counters to improve both momentum resolution and particle identification above 1 GeV/c. These Cherenkov counters are a recent development in which the rings of light emitted by the particles are actually measured. These counters promise to provide very clean particle identification.

The ALEPH project[17] is a collaboration of over 300 scientists from 25 institutions in 8 countries, under the leadership of Jack Steinberger from CERN. It is the largest time-projection chamber under construction. The ALEPH time-projection chamber, which is both the central tracker and the particle identifier, has an active volume of 43 cubic meters, seven times that of the PEP-4 detector. Each end has eighteen sectors with a total of about 50 000 channels of electronics, three times the number in the PEP-4 detector.

The time-projection chambers in both the ALEPH and DELPHI detectors are surrounded by photon calorimeters, which, in turn, are inside superconducting coils. The magnets are therefore very large, typically about 6 m in diameter and 7 m long, with fields between 12 and 15 kG. While this approach "wastes" some magnetic volume, it permits superior photon identification by minimizing the material in front of the photon calorimeter. Beyond their photon detectors, both ALEPH and DELPHI have hadronic calorimeters, which ensure that all the energy in the reaction is measured except for that carried away by neutrinos. This "missing energy" is a clear signature that separates many interesting physical processes.

The large construction efforts for ALEPH and DELPHI are backed by very large research and development programs aimed at optimizing the time projection chambers and the associated electronics. Time projection chambers that operate at atmospheric pressure, for example, present a different set of problems from those of pressurized chambers. Operating at one atmosphere simplifies the detector; the price paid is increased diffusion and decreased position resolution due to the effect on the electrons of the nonparallel electric and magnetic fields near the anode wires. Design details for the ALEPH and DELPHI time-projection chambers await the results of the research and development program.

New applications

Not all new time-projection chambers at work in high-energy physics are at electron–positron colliders. Physicists from the University of Genoa have tested a pair of time-projection chambers at CERN for a search[18] for beauty particles produced by 350 GeV/c pions in nuclear emulsions. The time projection chamber's role is to connect the visual information from the emulsion and the information provided by a spectrometer. Time projection chambers are the detectors of choice in this experiment because of their superior pattern-recognition abilities in crowded particle environments.

Time projection chambers have several novel applications outside of high-energy particle collisions.

One growing application is in the study of rare decays. The most advanced project of this class is the time projection chamber built by Michael Moe's group at the University of California, Irvine, to study double beta decay.[19] Particle physicists have studied double beta decay for several decades as a way to search for the nonconservation of lepton number. Nonconservation of lepton number would indicate the existence of a Majorana neutrino with nonzero mass or with right-handed currents in weak decays. The process can occur in two channels for a nucleus having atomic weight A and charge Z:

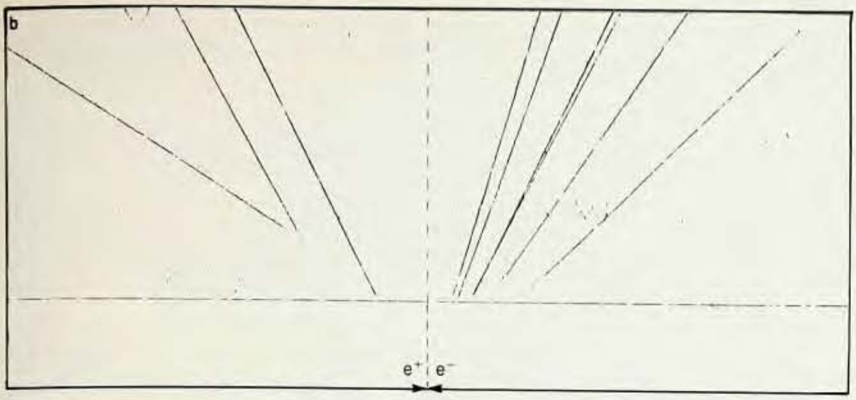
$$Z^A \rightarrow (Z+2)^A + 2e^- + 2\nu_e$$
$$Z^A \rightarrow (Z+2)^A + 2e^-$$

The second channel does not conserve lepton number and can be distinguished experimentally from the first channel because the sum of the energies of the two electrons is a constant.

Some evidence for the occurrence of double beta decay comes from geochemical analysis of rocks where the abundances of the nuclei Z^A and $(Z+2)^A$ are measured. Such analyses cannot distinguish between the neutrinoless and two-neutrino channels, and serve only as evidence that the process probably exists. The only direct evidence for double beta decay is from the Irvine group's cloud-chamber experiment, which had very limited statistics and produced a value of the halflife of Se^{82} in contradiction with the geochemical analysis.

The direct observation of double beta decay presents formidable difficulties. The expected halflives are in excess of 10^{20} years, and the decay releases energy comparable to that released by a great many other radioactive decays. Minute contamination by nuclei with much shorter lifetimes can lead to backgrounds that set the sensitivity limits in searches for double beta decay.

One way to reduce the backgrounds is to measure the trajectories and energy of the two electrons and to



Typical hadronic event as seen by a time projection chamber. **a**: View along the beam line in the PEP-4 detector, showing the pad-hits and the corresponding track fits. As indicated in the figure, all particles except for one are unabiguously identified by their ionization energy loss rate dE/dx. **b**: Projection of the wire data onto a plane containing the axis and one radius of the cylindrical chamber. Data from all six wedges appear. Tracks emanate from an electron–positron collision in the beam line. Figure 4

ensure that nothing else occurs in association with the decay. To track the electrons, the Irvine group has built a time-projection chamber in which the midplane electrode is a Se^{82} source. It has a drift length of 10 cm and a cross-sectional area of about 0.5 m^2. The gas is helium, which minimizes multiple scattering, and the device is inside a 700-gauss magnetic field. A successful test run of this detector suggests that the experiment will be able to study the lifetimes to the level of 10^{22} years. Running such experiments in deep mines helps minimize backgrounds associated with cosmic rays.

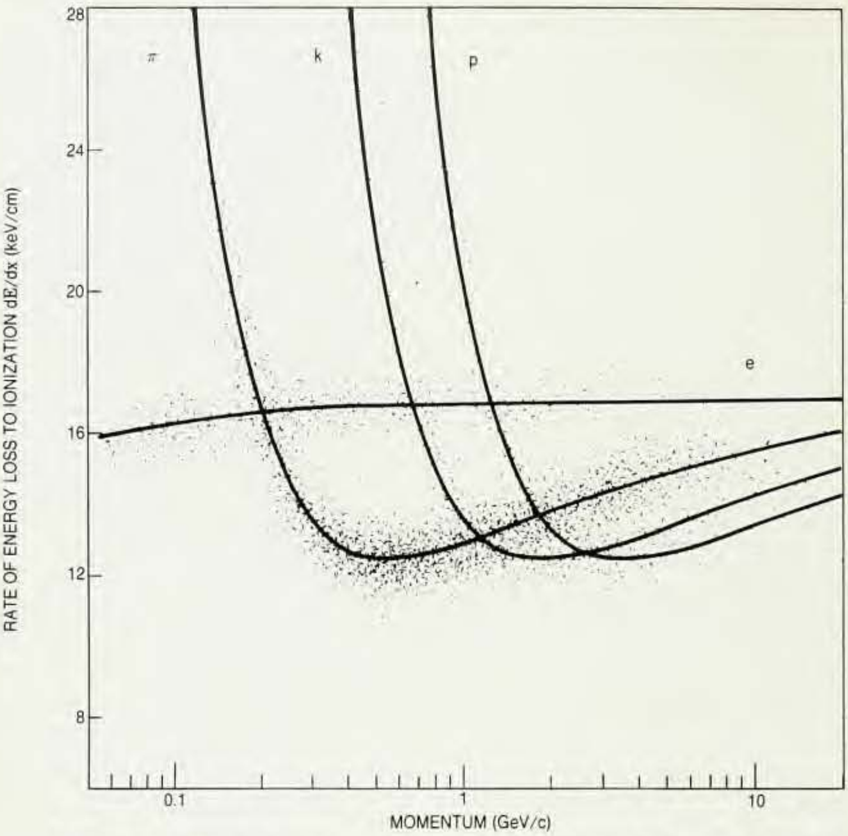
Two other groups, one at Caltech and one at the University of Genoa, are pursuing plans for studying double beta decay with xenon time-projection chambers.[20] These detectors require no source other then the gas itself, which is enriched with the appropriate isotope Xe^{136}. Both institutions have research and development programs aimed at optimizing this type of time projection chamber.

Another rare decay, if it exists at all, is proton decay. It may be the only window available through which we can test grand unified theories. The new particles called for by these theories are so massive—typically of order 10^{15} GeV—that their effect at energies we can reach with accelerators is truly minuscule. Thus we can look for their effect only in processes that would follow an absolute selection rule except in the presence of these massive particles. Such a rule is baryon number conservation, which nucleon decay would violate. Given the present experimental limits and theoretical expectations, new experiments must study nucleon decay to lifetimes of 10^{33} years or more.

The backgrounds once again set the limits on the lifetimes that one can study. The energy release of 940 MeV in proton decay is so large that radioactive backgrounds are not the problem. The limit is set instead by cosmic-ray neutrinos, which one cannot block no matter how deep a mine one chooses. A small fraction of the neutrino interactions mimic proton decay. One can minimize this background by maximizing the information gathered from each event. Massive time-projection chambers appear to be ideal for this purpose. In a 10 000-ton chamber, all tracks from nucleon decay would "range out," that is, the particles making the tracks would lose all their energy and stop, and all photons would shower and be absorbed. In each case one would learn the total energy by adding all the energy-loss-rate (dE/dx) samples. Furthermore, measurement of the total energy and of the energy for each track would identify the particles. These time-projection chambers would forgo magnetic fields; they must be compact to operate in mines. As a consequence, they also must operate at large densities, typically greater than 0.5 grams/cm^3.

Two groups, using different approaches, are tackling these technical problems. Herb Chen's group at Irvine is investigating liquid-argon time projection chambers,[21] and Oddone and Laszlo Baksay of the University of Dallas are working with ultra-high-pressure time-projection chambers.[22] The Irvine group has done beautiful work, demonstrating the ability of ionization trails to drift in liquid argon with attenuation lengths greater than one meter for drift fields of 1 kV/cm. Their instrument can measure tracks in three dimensions, and they are building a device to detect the initial scintillation light for timing purposes. The major remaining difficulties impeding implementation of a full-fledged liquid-argon time-projection chamber now appear to be of a practical nature: How to operate, deep underground, a large cryogenic system with very stringent requirements on the purity of the liquid.

One difference between liquid-argon time-projection chambers and the gas-filled detectors is that proportional multiplication of the drifted track of electrons has never been possible in liquid argon. The relatively small sig-



Scatter plot of rate of energy loss to ionization dE/dx versus momentum, for tracks in a sample of multihadronic events from electron–positron annihilation. The curves represent the predictions of theory for various particle types. Figure 5

nals, due to the lack of multiplication, place stringent limits on the attenuation of the ionization during drift and limit the energy resolution in large-electrode systems, in which electronic noise is more of a problem.

One way to have both the proportional multiplication that gases allow and the high density of liquids would be to operate with a gas at high pressure. Room-temperature argon at 325 atmospheres, for example, has a density of 0.6 grams/cm^3. Until last year, no proportional counter had operated above 170 atmospheres, and there were doubts that operation at much higher pressures was possible. The new ultra-high-pressure work has shown good proportional multiplication in argon with small amounts of methane up to 410 atmospheres, the largest pressure tested. The tests show an energy resolution of 15% for the 88 keV photon from Cd^{109}. Work this summer is aimed at demonstrating the operation of a small time-projection chamber at these high pressures. A full proton-decay detector could operate in a pressurized underground cavern or, if sufficiently high pressures are used, in hydrostatic equilibrium in deep oceans.

At the opposite end of the spectrum, Howel Pugh of LBL and his collaborators propose to miniaturize time projection chambers. They would like to use a small detector at a heavy-ion collider to detect strange baryons and their decays. The measurement of strange baryons would give information on the expected quark–gluon plasma. They propose using a time-projection chamber for this application because of its superb pattern-recognition ability—more than 100 tracks are expected in the collisions of interest. The miniature time-projection chamber would be 20 cm in diameter and have drifts of 10 cm. About 10 000 signals per event would be obtained from this small volume.

Time projection chambers are also helping to solve problems in the design of specialized counters. Peter Nemethy of New York University is proposing to measure or set a lower limit to the mass of the muon neutrino one order of magnitude better than previous measurements, down to the level of 50 keV/c^2. To make this new measurement one would study the decay $\pi \rightarrow \mu\nu$ in a tracking, imaging Cherenkov counter, which would make a very precise measurement of the pion and muon velocities. The time-projection chamber would be inside a high-pressure hydrogen Cherenkov counter to track the particles and reduce errors due to multiple scattering. In this configuration the gas in the time projection chamber is also the Cherenkov medium.

While future projects will extend the range of application of time-projection chambers, it is already clear that these detectors have come of age. The high-technology concept of ten years ago has now been added to the physicist's everyday toolkit.

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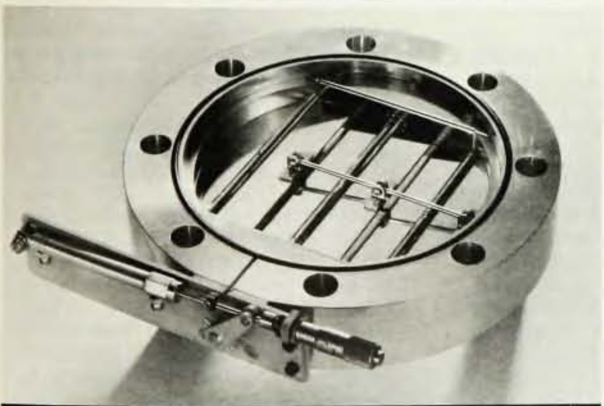

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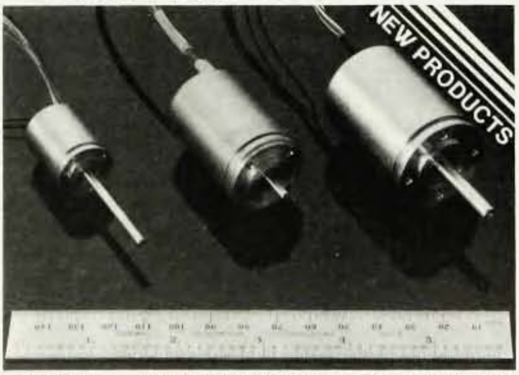

Operating Temp	125°C, maximum; 100°C, recommended; heatsinking required for continuous operation; bakeout temp 125°C, maximum		
Construction	4 phase, stainless steel case, variable reluctance motor		
Housing Size (Inches)	75 dia x 1.0 lg	1.1 dia x 1.7 lg	1.3 dia x 1.8 lg
Static Outgassing (Note 1)	0.5×10^{-7} Tl/s	1.0×10^{-7} Tl/s	1.4×10^{-7} Tl/s
Ultimate Pressure (Note 1)	1×10^{-9} Torr	1×10^{-9} Torr	2×10^{-9} Torr
Step Size	15°	15°	1.8°
Stall Torque (Note 2)	1.0 in oz	5.8 in oz	10 in oz
Dynamic Torque (Note 2)	0.6 in oz	3.2 in oz	6.0 in oz
Weight	1.5 oz	4.0 oz	6.0 oz

Note 1: At 25°C after 24 hr 125°C bake, non-operating. Operating outgassing rates and pressures depend on user supplied heat sinking, duty cycle, operating temperature, vacuum system, and driving electronics. In careful, baked UHV testing at PRI an ultimate pressure of 4×10^{-10} Torr was achieved with a size C motor and 140 l/s pumping speed. For intermittent operation (ie several minutes at a time) outgassing rates and pressures are within a factor of 5 of the non operating values. For continuous operation, ask for PRI application note.

Note 2: 2 phase excitation at full power.

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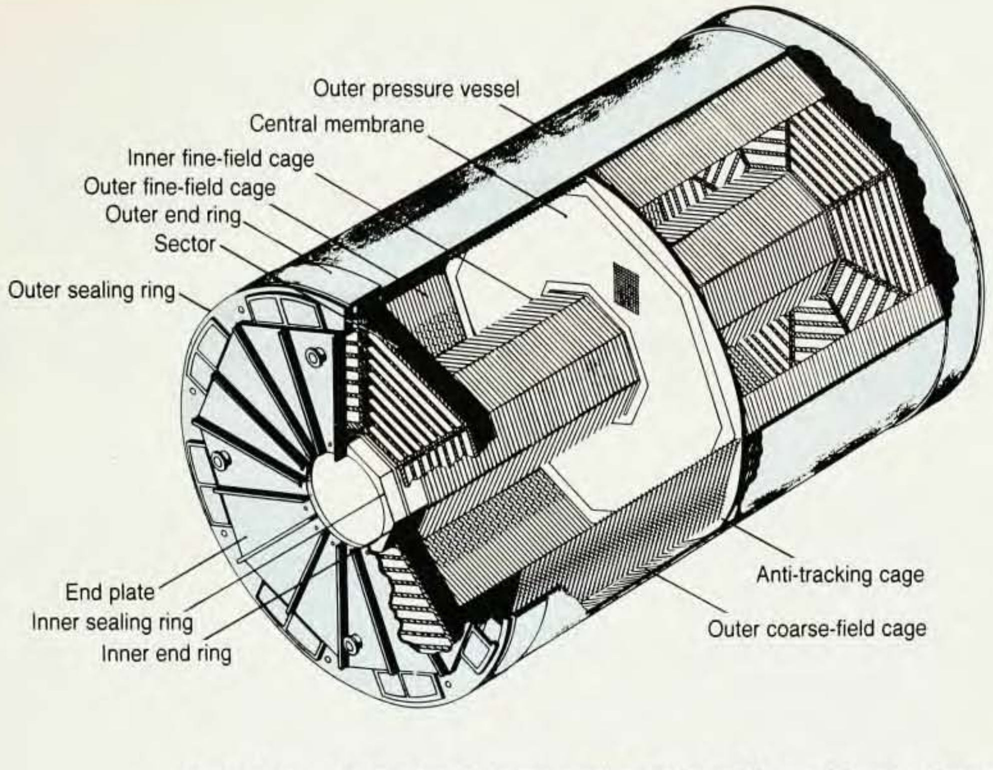

The TOPAZ detector. This time projection chamber is being built by a collaboration of groups in Japan. The inner and outer insulators double as the inner and outer pressure vessels. Figure 6

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