The Time-Projection Chamber - A new 4π detector for charged particles

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Abstract

A new approach to the problems of track recognition and momentum measurement of high energy charged particles is described, and a detector particularly suitable for PEP energies is discussed.

The central idea is the utilization of a large methane-filled drift chamber placed in a strong magnetic field, with the drift field oriented <u>parallel</u> to the magnetic field. In this configuration transverse diffusion of the ionization electrons can be very substantially suppressed by the magnetic field. This in turn leads to the possibility of measurement accuracies on the order of 100 microns after one meter of drift.

At the same time, the detector can provide truly 3-dimensional spatial data, free from the ambiguities characteristic of conventional techniques involving spatial projections. The reconstruction efficiency can be expected to approach 100%, even for events of the highest multiplicities.

Introduction

The existence of a charged particle detector which could provide simultaneously the capabilities of 50 to 200 micron spatial resolution throughout a large volume, $\simeq$100% pattern recognition and reconstruction efficiency over 99.5% of 4π, good time resolution, fast recovery after triggering, digital readout of data, compatibility with high magnetic fields, and reliability in operation, would represent a very substantial advance in detection techniques. These characteristics should be realizable in the time-projection chamber, (TPC) a concept well-suited to the experimental problems posed by much of the interesting physics expected at PEP energies.

In the PEP environment, a fairly compact detector can be envisaged for measurements of the total cross-section for e^+e^- annihilation to hadrons, momentum spectra of charged secondaries from 50 MeV/c to 15 GeV/c, for the study of jet structures and other correlations, strange particle production, etc. The detection of neutral component by other techniques would be aided by the compactness of the envisaged detector.

Basic Concepts

An electron in a gas diffuses by thermal agitation in the absence of other forces, and this diffusion from an ideal point source of electrons, after a time T is given by

$$\sigma = \sqrt{2DT} \tag{1}$$

Here σ is the rms normal distance to an arbitrary plane containing the electron source. D is a diffusion coefficient, which depends on the particular gas, the number density and the electron temperature. The diffusion coefficient D is in fact equal to $V\ell/3$, where V is the electron speed and ℓ is the electron mean free path in the gas. The introduction of an electric field does not appreciably change the diffusion properties, provided that the energy gained from the electric field by the electron between collisions is appreciably transferred by inelastic processes to the molecules of the gas.

In the case of pure noble gases, however, only elastic collisions occur for moderate values of E/p (electric field/pressure in units of volts/cm-torr) and the effective electron temperature can be driven to hundreds of times the thermal value. Therefore, the use of polyatomic gases which keep the electron temperature low (and hence D low) is essential for high resolution drift chambers.

Charpak et al.[2] have obtained experimental results for a mixture of 75% argon-25% isobutane and found agreement with equation (1), with σ values of $\approx$120 microns a drift distance of 1 cm. It is worth noting that, due to the square root in (1), the rms resolution expected after a meter drift is only 1.2 mm.

Further experimental results have been obtained by a Saclay Group[3] for methane. In this work, the resolution obtained for a 50 cm path was 540 microns. Extrapolation to one meter gives 760 microns, a useful but not exceptional resolution. Methane also possesses the highest known[4] electron mobility, defined as the ratio of the electron drift velocity W to the applied electric field E:

$$\mu = \frac{W}{E} \tag{2}$$

The question naturally arises: can the resolution be improved? The surprising answer is yes. This can be achieved by capitalizing on the possibility of substantial suppression of the electron diffusion caused by the presence of a superimposed magnetic field parallel to the electric drift field. The mechanism of diffusion suppression is quite simple: the electrons execute helical orbits around the field lines, and if the radius of the typical orbit is small compared with the mean free path, then diffusion transverse to the fields is effectively suppressed.

It should be noted that the longitudinal diffusion, i.e. diffusion along the field direction, is unaffected by the magnetic field. In fact, at the relatively large values of e/p characteristic of drift chamber operation[5], differences in the parallel and transverse diffusion coefficient may occur due to increased electron temperatures.[6] This latter effect depends mainly on the properties of the particular gas involved.

For the case of diffusion transverse to a magnetic field, theoretical analysis leads to the following expression[7]

$$\sigma_{\perp}^{2} = \frac{\sigma_{\parallel}^{2}}{1 + \omega^{2}\tau^{2}} \tag{2}$$

Here $\sigma_{\perp}$ is for diffusion transverse to the fields, $\sigma_{\parallel}$ is given by (1), ω is the cyclotron frequency eB/m_e, and τ is the electron mean collision time. Clearly, we want to have $\omega\tau >> 1$. The mean collision time τ is given to a good approximation[8] by

$$\tau = \frac{\ell}{V} = 1.09 \times \frac{M_e}{e}\,\frac{W}{E} \tag{3}$$

indicating that only gases with high mobilities are appropriate candidates. In fact, methane is apparently far superior to any other gas in this regard.

The data available[9] for pure methane implies a maximum drift velocity of 12.5cm/μsec at an E/p of 1.0 corresponding to an E of ~760 volts/cm (Fig.1). This value is substantially higher than that found in the work of the Saclay group[3], in which a drift velocity of 9.7cm/μsec was observed at an applied field of 830 V/cm at atmospheric pressure, E/p $\simeq$ 1.1. Taking a conservative viewpoint, the mobility implied by figure 1 will be assumed to be optimistic by 20%. This leads to a mobility μ of (10 cm/sec)/(675 Volts/cm) = 1.5×10^{-2} cm^2/Volt-sec, and a mean collision time, using (4), $\tau = 9.2 \times 10^{-12}$ sec. For methane under these conditions, $\omega\tau = 1$ for a field of 0.618 T. While this is a conservative estimate, it is nonetheless clear that large fields are needed for an appreciable affect.

An example of a possible TPC detector configuration suitable for PEP is shown in Figure 2. A cylindrical gas volume surrounds the luminous region (penetrated of course by the vacuum tube). In the plane normal to the beams and intersecting the center of the luminous region, a screen or foil establishes a uniform electric field parallel to the beams. Obviously, guard rings to grade the field properly and appropriate insulation must be provided to isolate the beam tube and outer walls. As the voltages are in the neighborhood of - 60KV, the additional thickness around the beam tube necessary for the HV insulation will be on the order of 3 mm and can be tapered as the voltage decreases near the ends.

A field of 3.33 T has been chosen in this example. The diffusion is reduced according to (3) by a factor of 5.5 leading to an expected σ of 130 microns for a 90 cm drift path (σ = 720 microns). Thus, one obtains resolutions in a volume the order of a cubic meter which are characteristic of the resolution obtained in a cubic centimeter!

Specifically, the proposed TPC detector will operate as follows. High energy charged particles penetrating this volume experience magnetic deflection and leave ionization trails in the gas. These ionization electrons drift toward the relatively positive end cap. Eventually, the entire image of each trajectory falls onto the end cap, where the information can be read out.

In this example, the maximum drift time is given by 90 cm/(9.7 cm/ μsec) = 9.3 μsec. This time interval corresponds to 3.9 PEP bunch periods, so that the detector is unfortunately sensitive to background induced by the equivalent of three more bunches (2.4 μsec/bunch), in addition to the unavoidable background associated with the bunch giving rise to the real reaction of interest. Later, it will be argued that this background burden is not expected to be a serious problem.

End Cap Detectors

A. Pattern recognition

As discussed above, the information contained in the ionization trails can be translated to the end caps without serious degradation. The solution for the readout of this information presents a number of possibilities, only one of which will be discussed here in any detail. The most important point in this regard is to note that the possibility exists in the time projection chamber to obtain truly 3-dimensional spatial data. The absence of the ambiguities associated with spatial projections should have an enormously beneficial impact on the problem of pattern recognition in high multiplicity events.

To explore how this capability might be realized, consider an end cap detector composed of a honeycomb structure of cells, each about 1 cm in diameter. Each cell is assumed capable of giving a pulse related to the time of arrival of any electrons drifting into its active area. The basic data then consist, for each track, of a string of numbers x_i, y_i, $z_i \equiv W(t_i - t_o)$, where x_i, y_i describe the cell location in the end cap plane and z is given unambiguously by the measured drift time and the known intersection time t_o. (A trigger of some kind is needed of course). Thus, as the projection is in time, not space, the familiar ambiguities are absent.

A one centimeter diameter cell gives a rms spatial measurement of ~ 3 mm, so that useful momentum measurements are not obtained directly from this information. However, the problems of pattern recognition have been reduced to a very simple task: every real track should give a contiguous string of hit cells, with roughly similar spacing in drift time. A simple small computer, without any pattern-finding manipulations, can show event candidates in 3-dimensions, using stereo angles appropriate to human perception. Figure 3 shows a 2-dimensional view of a "typical event" of multiplicity 12.

An associated point worth emphasizing is the very wide dynamic range of momenta accepted by the time-projection chamber. For a 10 cm diameter beam pipe and a field of 3.33T, particles of transverse momenta from 50MeV/c to the full 15 GeV/c will be registered and easily recognizable.

The number of cells in each end cap for 1 cm diameter size would in practice be about 8000 for 100% coverage over a 1 meter diameter. Each cell required a 200 MH_z equivalent scaler with fast buffering so that tracks which cross in the x,y plane and low momentum tracks which spiral within the active volume can be read out completely. In the example chosen, particles with transverse momenta below 220 MeV/c will be contained within the diameter of one meter.

It is also noteworthy that δ rays should not lead to any difficulties in pattern recognition. This is because the radius of curvature is smaller than a cell size for nearly all δ ray energies. Specifically, a 5 MeV/c electron has a radius of curvature of 5 mm. The probability of producing a δ ray with this or greater energy in the gas is about 5×10^{-4}/track. However, scattering at these energies is severe, and multi-mev δ rays will likely "knock out" several cells as they spiral down the chamber. δ rays produced in the walls are driven by the magnetic field back into the walls immediately. More likely to be a nuisance are δ rays on the order of a few hundred KeV, which are produced more copiously and by scattering manage to affect more than one cell. A very rough estimate suggests that bad information occurs at a rate less than 2×10^{-3}/cell. Thus the inescapable occurrence of δ rays should not lead to noticeable degradation of pattern recognition, in contrast with experience with other large solid angle devices such as the CERN ISR split-field magnet facility.

B. Momentum Resolution

Here, much study is necessary before an accurate statement can be made. Nevertheless, a naive comparison with present techniques is instructive.

For example, if the measurement error of the TPC cells is assumed identical to that each of 3-conventional drift chambers in a cylindrical geometry of the same diameter then the larger number of measurements/track in the TPC leads to an improvement[10] in $\Delta p/p$ of 2.5, a modest factor. However, compared with typical non-superconducting solenoid fields like .5T, the higher field of 3.3T yields another factor of 6.6, for a total improvement in $\Delta p/_p$ of ~16 relative to currently considered approaches such as the "mini mag" proposal.[11]

At present this point it is appropriate to discuss more specifically what the properities of the cells might be in practice. The author has constructed cells of the sort shown in Figure 4, with good results. A one-mil diameter platinum wire is embedded in a recessed plastic insulator, which positions the wire along the axis of a copper tube. The tube is open at one end, through which the platinum wire is exposed for about 1 cm. By means of a high temperature flame, the end of the wire is easily melted to form a smooth ball of slightly larger diameter; the ball inhibits gas breakdown by reducing the local electric field. By applying suitable electric fields across the tube and central wire, this ball-wire cell behaves very much like an ordinary proportional counter. Quite large pulses, even from single electrons, can be obtained (Fig. 5). The radius of sensitivity has not yet been determined, but can be expected to depend on the extent of protrusion of the wire beyound the tube opening, the ratio of the radial field in the tube to the drift field etc. Simple electrostatic considerations indicate that the cell should be sensitive over nearly all of its frontal area. In fact, work on a so-called "needle chamber" has been recently reported,[12] in which a drift field is arranged to terminate on a matrix of needles. The field at the tips of the needle is sufficiently high to give multiplication. The advantage of the additional outer conductor in the TPC end cap detector is that the drift field and the multiplication field can be separately optimized. Also, the ball-wire detector is sensitive over most its exposed length, leading to higher efficiency.

Turning now to the response of the ball-wire cell to a track image, the first point is that the cells have azimuthal symmetry so that the response will not vary with the track image's local azimuth angle. Consider a electron reaching the end cap region: nearing the cell, the electric field gradually changes from a longitudinal field to a radial (i.e., transverse) field around the wire. To reach the wire, the electron must cross magnetic field lines. The extremely strong ExB force leads to a spiral trajectory, in which the electron "radial velocity" is effectively slowed by a large factor:[7]

$$W_{\perp} \simeq \frac{W}{\omega\tau} = \frac{W_{\parallel}}{\omega\tau} \tag{5}$$

Thus the measured time at cell # i can be written as the sum of two conceptually distinct components:

$$t_i = \int_{z_i}^{L} \frac{\vec{z}\cdot ds}{W} + \int_{z_i}^{L} \frac{\vec{r}\cdot ds}{W} \tag{6}$$

where $\vec{r}$ is a radial unit vector from the i^{th} wire to the trajectory. For clarity, eq.6 can be rewritten approximately as

$$t_i = \frac{(L - Z_i)}{W} + \frac{b_i}{W} \quad , \tag{7}$$

where b_i is the "impact parameter" of the initial track image projected onto the i^{th} cell.

Thus, for the purposes of exact track reconstruction and momentum measurement, a limited ambiguity exists in the basic time data. A further complication is introduced by the polar angle of the track image, which can lead, for very small polar angles, to track segments with larger impact parameters actually giving pulses before the track element with the smallest impact parameter.

On the other hand, each track is measured up to 40 times, so that the available information is probably sufficient to untangle these ambiguities with serious degradation of resolution. As of this writing, the author has not yet attempted to find algorithms for doing so, and the possibility of potentially serious difficulties here must be recognized.

It should also be noted that the ambiguities discussed above can be removed by the use of additional detector elements such as rings of short proportional wires in the plane of the end cap which determine the polar angle of the tracks and the vertex in the luminous region. In this "hybrid" approach, the ball-wire cells would provide the pattern recognition and momentum measurement capabilities, but not the longitudinal measurements.

Other quite different endcap schemes can be envisaged, such as rings of needles, with very close spacing so that the impact parameter b is negligible. Or rings of short wires can be introduced, with current division used along the wire to obtain 3-dimensional data.

It is worthwhile to note that the 200 MHz clock rate corresponds to a rms longitudinal resolution of 144 microns, whereas a transverse resolution of 27 microns is obtained due to the reduced transverse velocity.

The ball-wire cells display a resolution $\sqrt{2}$ poorer than the 130 microns quoted earlier because the measured time is the sum of the longitudinal + transverse drift time. Other readout schemes need not suffer this degradation. Inclined tracks can display an improved resolution since the drift paths will average less than the maximum. For an ideal detector the resolution of the TPC should scale as

$$\frac{\Delta p}{p} = \frac{\text{Gas density}}{B^2 R^2} \tag{8}$$

where R is the radius of the detector.

Discussion

A. Particle Identification

It is interesting to speculate on the possibility of charged particle identification using the dE/dx information available in the ionization trails arriving at the end caps (Fig. 6). This technique of particle identification is under development for application at BEBC and possibly other installations.[13] Based on their results in an argon 95% - methane 5% mixture, a 2 meter path length in gas, sampled every centimeter gives a 5% rms measurement of dE/dx, more than sufficient for the purposes of π/K and K/p separation in the few GeV/range. The compact TPC with a .5 meter radius may be too small for this technique to be successful at the highest energies.[14]

B. Backgrounds

The main component of electron-positron colliding beam backgrounds is generally thought to be low energy γ rays from showers initiated by scattered particles from the beams. As discussed earlier in the section on δ-rays, low energy electrons give tightly contained orbits: 15 MeV/c corresponds to a radius of curvature 1.5 cm, 15 KeV/c of only 15 μ. The small amount of matter in the sensitive volume, methane gas at ~ 7.1×10^{-4} g/cm^3), should minimize the conversion rate. Because of the 3-dimensional quality of the basic information, isolated "noise" should present no problem unless the rates actually lead to total ionization levels competitive with that of real events. Probably no detector except an absorption device can operate in such an environment. Occupancy rates for the beam pipe counters at SPEAR I are on the order of 0.01, so it is reasonable to expect this background may be quite manageable.

The 3-dimensional quality of the basic data should allow the easy recognition and rejection of unrelated tracks. A background track must verticize within a few mm of the real event vertex in order to escape rejection, a very unlikely occurence.

One of the potential weaknesses of the TPC must be emphasized here, namely, that background from 3 additional bunches must be accepted. Whether this amounts to a serious problem in practice cannot easily be predicted, although conventional detectors would probably be unable to operate effectively in background levels which would limit the TPC.

C. Data Rates

For a typical e^+e^- annihilation event at PEP energies, one might expect 10-20 charged tracks. If each of 20 tracks gives signals on 40 cells, then the number of bits recorded is about 21,000 per event, or 650 32 bit words. This corresponds to $\gtrsim$2000 events/tape. Real events contribute a very small total rate, so that the actual rate is determined entirely by the looseness of the trigger.

D. Present Program

The measurement of the transverse diffusion in methane, with and without a magnetic field is underway. Results from these experiments should show what resolution can be expected under realistic drift chamber conditions. A diffusion measuring device has been constructed and operated with argon filling. The results indicate a substantial space-charge induced broadening of the electron swarm. Further tests showed that the instantaneous beam current was >1000 times higher than the average current, caused by spontaneous pulsing of the field emission source. The device is presently being fitted with a UV-photoelectric effect electron source to alleviate this problem.

Work on Monte Carlo simulation is beginning. Optimization of the ball-wire cell geometry is continuing. I would like to thank Dr. Steve Shannon for his interest and assistance in many aspects of this work.

References

1. D. R. Nygren, "Proposal to Investigate the feasibility of a Novel Concept in Particle Detection", LBL internal report, February 1974.

2. G. Charpak, D. Rahm, and H. Steiner, Nuc. Instr. and Meth. 80, 13 (1970); G. Charpak; F. Sauli, and W. Duinker, Nucl. Instr. and Meth. 108, 413(1973).

3. J. Saudinos, J. C. Duchazeaubeneix, C. Laspalles. and R. Chaninade, Nucl. Instr. and Meth. 111, 77(1973); J. Saudinos, "Operation of Large Drift Length Chambers", in Proceedings of the Frascati Conference on instrumentation p.316(1973).

4. At least a search of the available literature has not revealed a superior gas.

5. E is typically 500 to 1500 volts/cm, at atmospheric pressure of 760 Torr, so that $E/p \simeq .7 - 2$.

6. J. H. Parker and J. J. Lowke, Phys. Rev. 181, 290(1969).

7. See, for example, J. S. Townsend, "Electrons in Gases", Hutchinson's Scientific, London, 1948; S. Brown "Introduction to Electrical Discharges in Gases", John Wiley and Sons, N.Y., 1966; L. G. H. Huxley and R. W. Crompton, "The Diffusion and Drift of electrons in Gases", John Wiley and Sons, New York, 1974.

8. J. S. Townsend, op. cit. p.11.

9. G. S. Hurst, J. A. Stockdale, and L. B. O'Kelley, J. Chem. Phys. 38, 2572(1963).

10. R. L. Gluckstern, Nucl. Instr. and Meth. 24, 381(1963).

11. A proposal for Separ II prepared by members of Group A and others at LBL.

12. C. Grunberg and J. LeDevehat, Nucl. Instr. and Meth. 118, 457(1974).

13. W. W. M. Allison, C. B. Brooks, J. H. Cobb, J. N. Bunch, J. L. Lloyd, R. W. Pleming, Nuclear Physics Laboratory Report 17/74 Oxford University; M. Aderholz, P. Lazeyrus, I. Lehraus, R. Matthewson, W. Jejessy, Nucl. Instr. and Methods, 118, 419(1974).

14. Ambiguities exist at three momenta where the dE/dx curves for pions, kaons and protons cross one another. See Fig. 6.

Figure Captions

1. Drift velocity of electrons in methane as a function of E/p, from ref. 9.

2. Schematic design for a TPC detector for PEP. Detection of neutrals has been omitted in this example.

3. A "typical" event (shown in 2 dimensional projection, looking along the beam pipe).

4. Construction details of the ball-wire cell detector used in initial tests.

5. Pulses obtained from single electrons. The gas employed was argon-isobutane, 80-20%, with a small percentage of methylal. The termination is 100 ohms. Voltage - 1100V. Under these conditions, no small pulses occur.

6. DE/dx curves versus momentum (for Argon 70% CO_2) from Allison et al., Ref. 13. The equivalent curves for methane would be very similar.

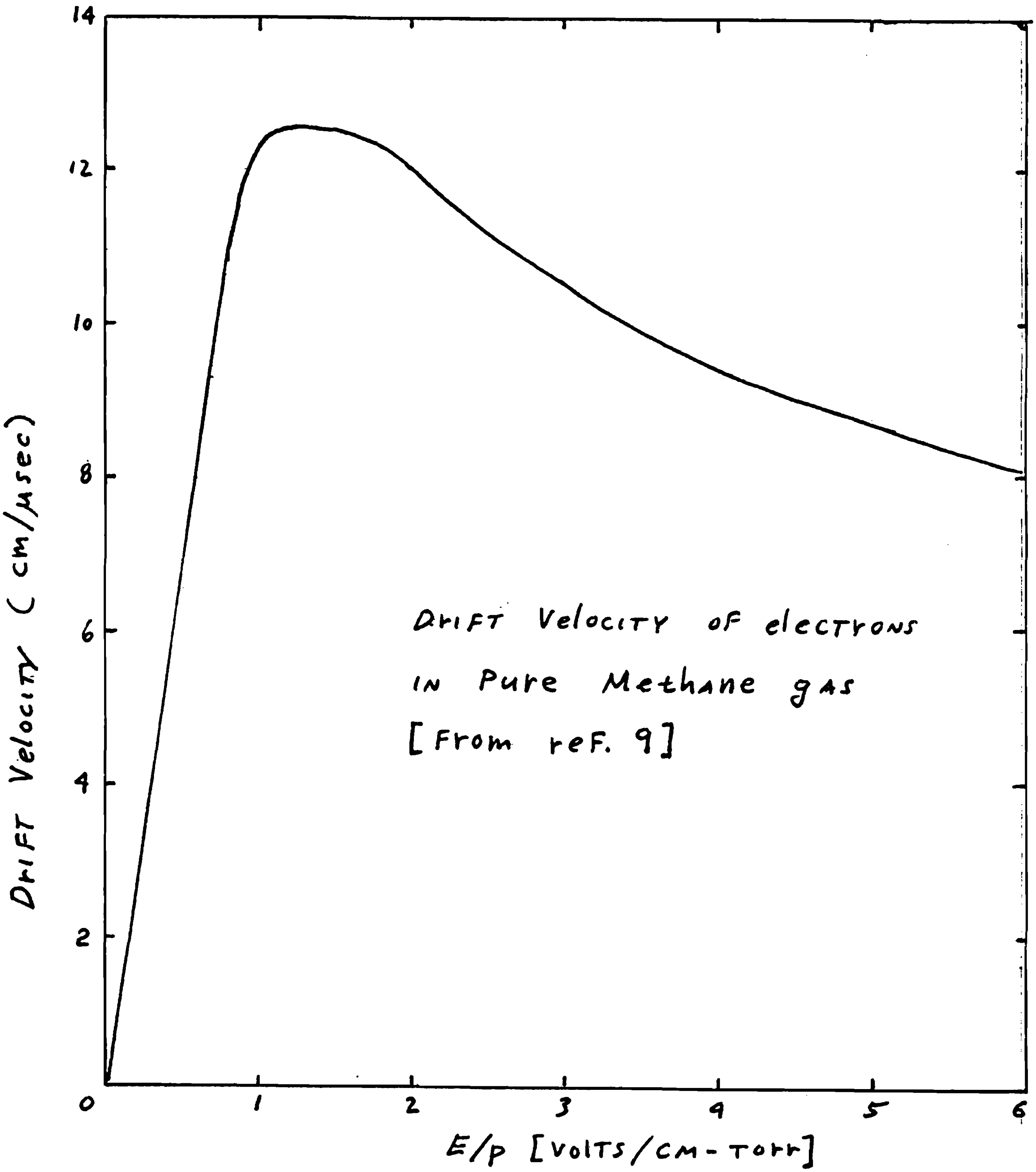
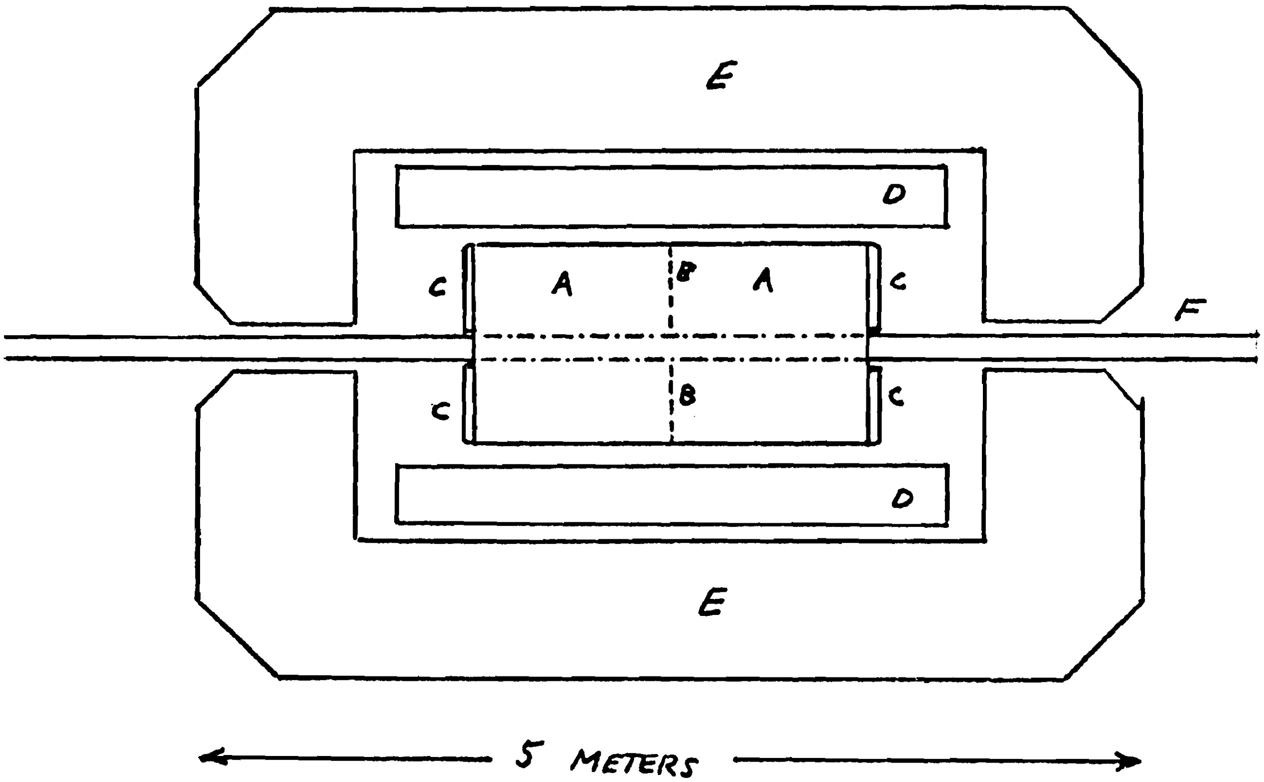

14
12
10
8
6
4
2
0
Drift Velocity (cm/μsec)
Drift Velocity of electrons
in Pure Methane gas
[From ref. 9]
1
2
3
4
5
6
E/p [volts/cm-Torr]

Figure 1



A. Methane-Filled region ~1 M dia., 2 M Length

B. Screen or Foil to establish $\vec{E}$ Field

C. End-cap detectors

D. Superconducting Solenoid (3.33 T)

E. Iron return yoke for B field

F. Beam Vacuum Pipe.

Not shown are trigger scintillators, compensators luminosity monitors, etc.

FIGURE 2 TPC Detector Schematic

TPC IMAGE USING DIRECT CELL DATA.

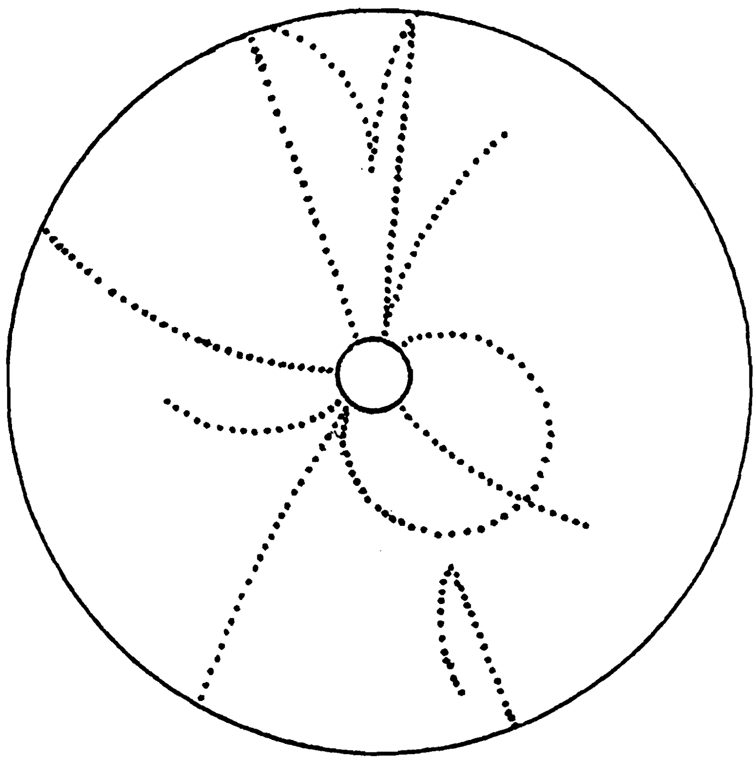


Figure 3 "Typical event" with 12 CHARGED TRACKS, SHOWN IN 2-DIMENSIONAL PROJECTION. Some event tracks leave through the end caps.

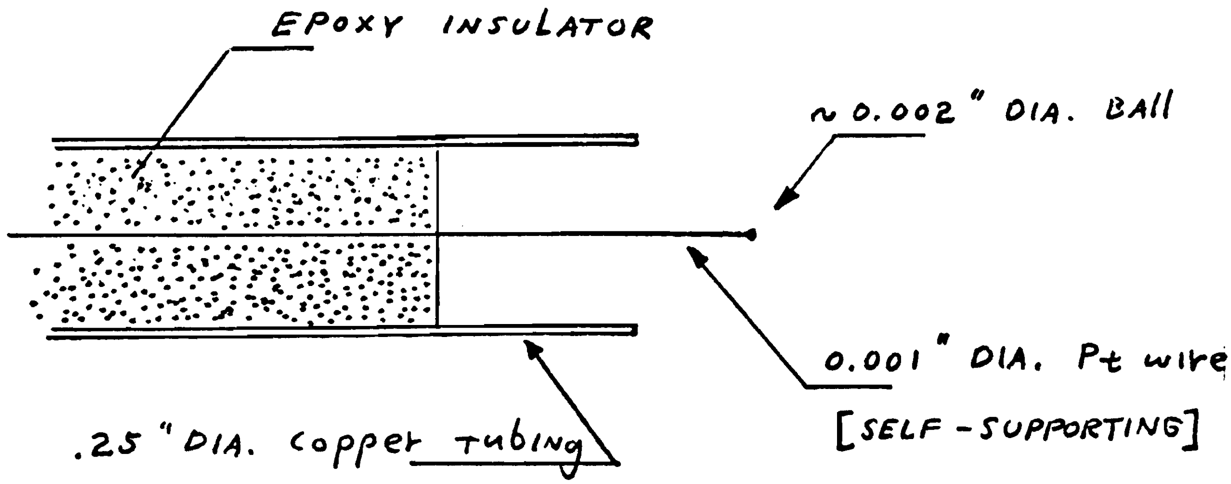
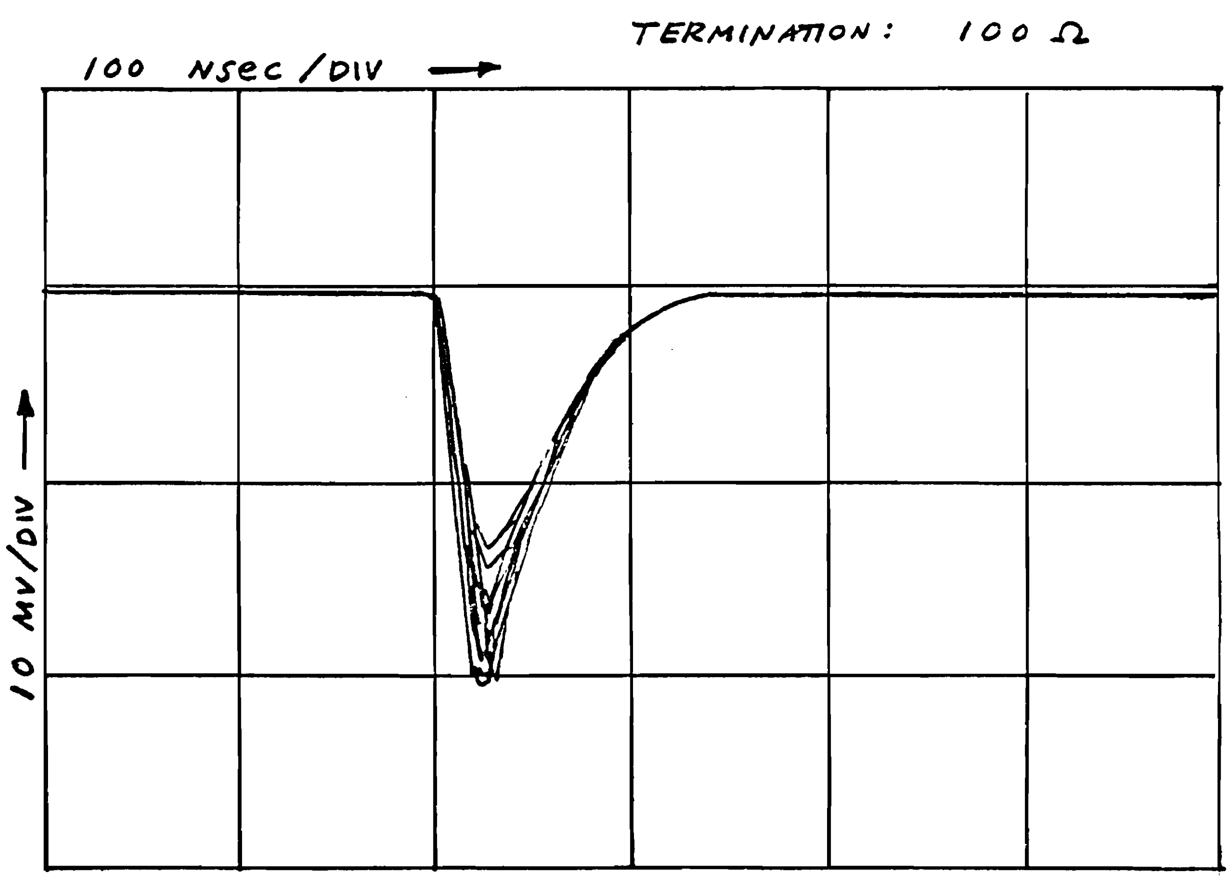


Figure 4. CROSS SECTION OF BALL-WIRE Cell

Figure 5. SINGLE-ELECTRON PULSES FROM Cell



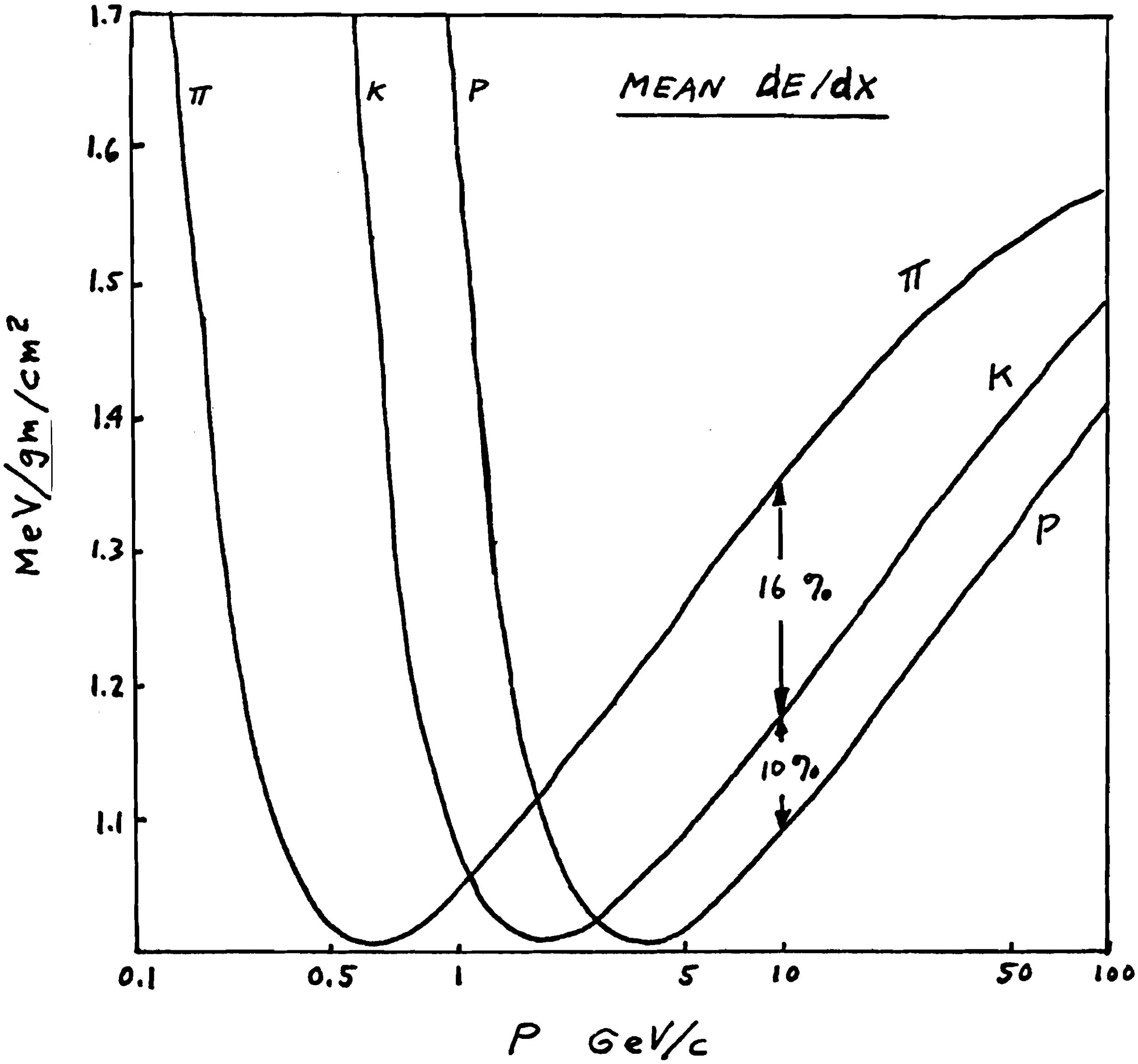


Figure 6. DE/DX variation with P
For π's, K's, P's