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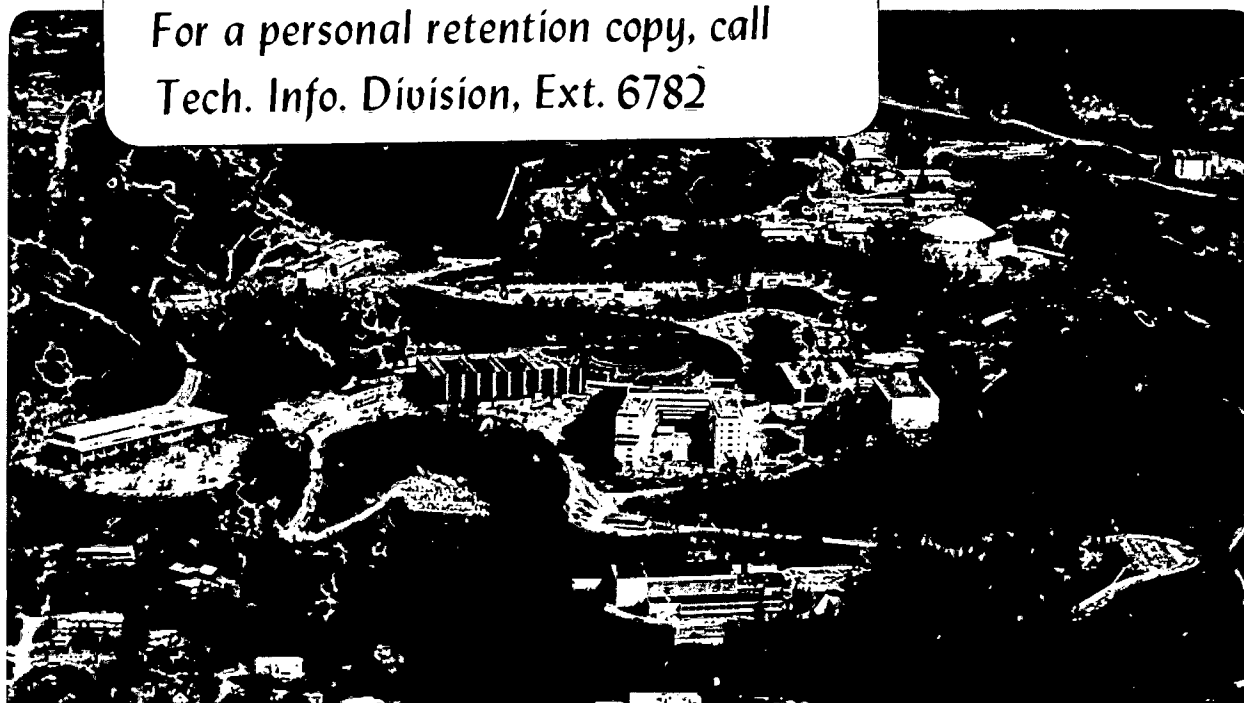
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Abstract

The Time Projection Chamber (TPC) is a large gas filled cylindrical detector designed to provide 3-D images of tracks radiating from the center of the detector where e^+e^- collisions occur. Ionization along the tracks is drifted in an electric field to the end planes which are equipped with a large array of proportional wires and position pads (17,000 channels). The wire signals are used to derive radial data while the pad signals provide the azimuthal information. The axial dimension is determined using the drift time of the ionization. Preamplifiers mounted in the ends of the chamber feed the signals to remote amplifiers whose outputs drive Charge Coupled Devices (CCD). The CCDs are normally clocked at 10 MHz and hold a 45.5 μ s history (445 CCD buckets) of analog drift information from the TPC. During readout the clock is changed to 20 KHz and 17,000 CCD outputs are digitized (9 bits) in parallel. The non-zero data is then transferred to buffer memories associated with the digitizers. This paper emphasizes the analog signal processing part of the system.

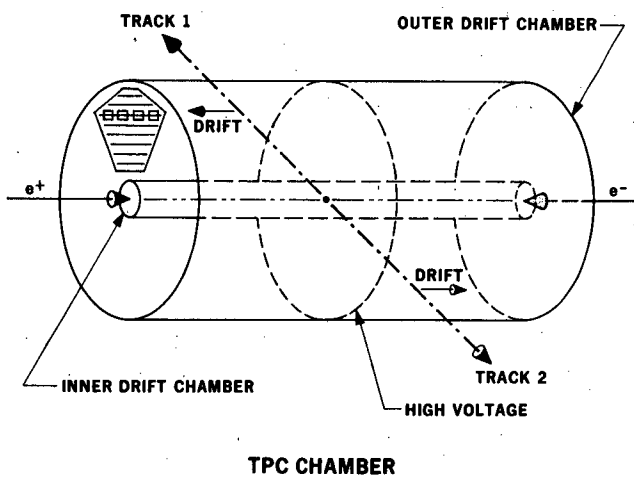
Introduction

The Time Projection Chamber¹ shown in Fig. 1 is a large gas filled detector designed to provide a three-dimensional image of the tracks of reaction products of e^+e^- collisions. The cylindrical detector, one meter in radius and two meters long, is contained in a pressure vessel containing Argon (80%) and Methane (20%) at 10 ATM pressure. A uniform electric field drifts electrons to both ends of the chamber. The field is produced by applying high voltage between a conductive central plane membrane and field gradient rings on the wall of the cylinder. Electrons reaching the ends of the cylinder pass through a Frisch grid plane and are amplified and sensed by proportional wires and position pads located on sectors.

An illustration of a sector is included in Fig. 1. Each end plane is split into six sectors. Proportional wires (a few of 185 shown) are spaced from the inner to outer radius on 4 mm centers and are aligned as chords. Pad rows (one of 15 is shown) are located along under 15 of the proportional wires in each sector. The wire signals provide both timing and amplitude information. Signals are induced in the pads by the charge produced in the multiplication region near the wire; by interpolation between pad signals, the centroid position of the charge along the wire can be determined.

The geometric design is chosen to determine the ionization along approximately 4 mm radial track increments. For minimum ionizing particles about 200 electron/ion pairs are produced in a 4 mm track increment. A gas gain in the range of 1000 to 2000 can be achieved at the proportional wires resulting in a total charge of 2 to 4 $\times 10^5$ electrons. Since only about 30% of these are sensed by the electronics in the measurement time the effective wire signals lie in the approximate range 5 $\times 10^4$ to 10⁵ electrons.

The RMS fluctuations (primarily due to Landau collisions)² in the number of electrons per 4 mm sample is approximately 32%. To achieve no more than 10% degradation in this spread the effect of electronic noise must be less than 14% of the signal (i.e., about 10⁴ electrons RMS). When signals from 185 wires are added to determine the total energy loss along a track the resulting RMS spread in energy determination is about $(35/\sqrt{185})$ percent or 2.5%.



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Fig. 1. Schematic of the Time Projection Chamber

The timing of the signals at the wires with reference to the beam crossover are used for assignment of wire signal to specific tracks. Specifically the centroids of the electronic signals from the wire amplifiers are measured. A position accuracy of ± 2 mm calls for ± 30 ns time resolution for an electron drift velocity of 7 cm/ μ s.

Pad signals are induced by the residual positive charge existing near a proportional wire in the gas when the electrons are collected at the wires. The maximum signal is induced on the pad directly beneath the point of the avalanche on the wire and falls off for pads away from this point. Therefore, determining the centroid of the pad signals along a wire determines the position of a track crossing the chord of a pad row. Since 15 pad rows exist, pad signals define 15 points along a track. An axial magnetic field is used in TPC, so the 15 pad row crossings can be used to derive the radius of curvature of a track (i.e., the momentum of a particle). In the absence of noise the spreads due to track diffusion and the effects of mechanical misalignment set a lower limit of ~ 100 μ m for the pad position resolution. This translates to a required signal to noise ratio of $\sim 1.6\%$. Signals induced on the pads are approximately one half of those quoted earlier for the wires and, therefore, are about 3 $\times 10^4$ electrons. Electronic noise is a major factor in determining the accuracy of position measurements along a pad row. Timing of the pad signals is

also determined. The computer software uses the pad data to determine the track trajectory and then assigns the wire data to the trajectories.

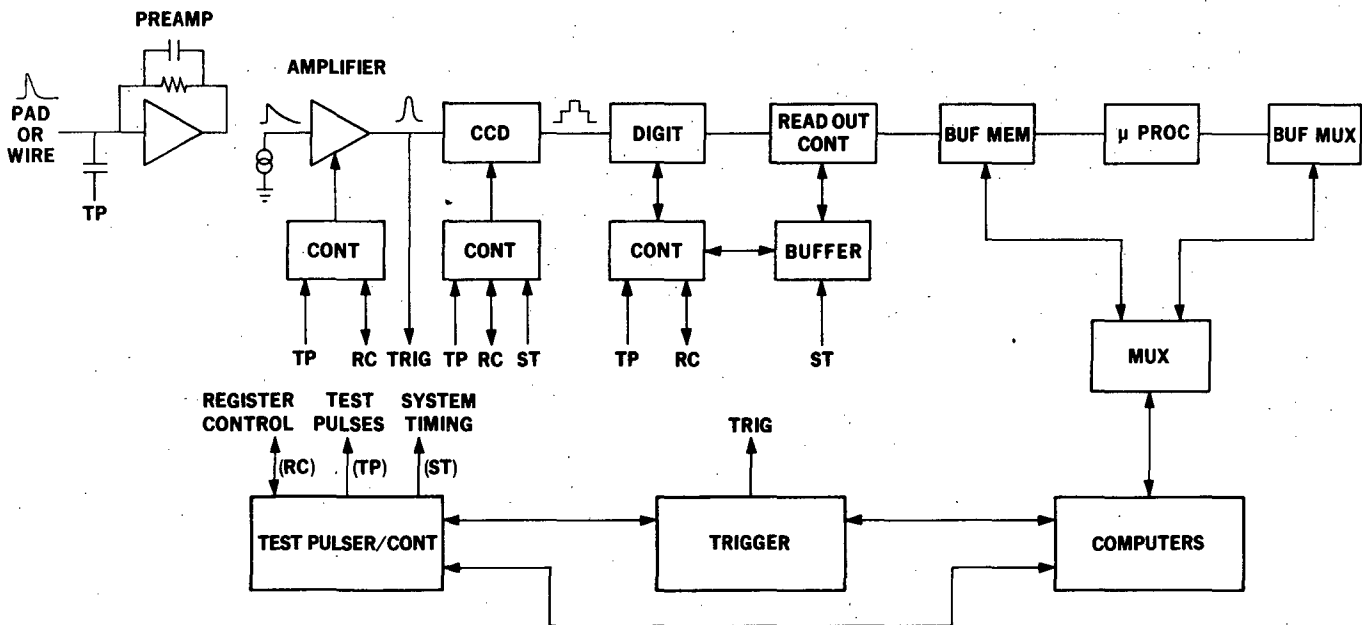
The time to drift all tracks from the chamber is 15 to 30 μ s. The electronics must record all pertinent information from the TPC during this drift time. Many interesting events have multiple tracks within a cone of 60° (jets). Therefore, recording of such bursts of information must be handled by the electronics. Linear analog CCD shift registers (Fairchild 321A*) are used to achieve this.

Electronic System

An overview of the electronic system is shown in Fig. 2. Signals from the wires or pads feed charge sensitive preamplifiers located on the back side of the sectors within the gas volume.³ The close proximity of the preamplifiers to the signal source reduces input capacitance and thereby improves the signal-to-noise ratio. Mounting the preamplifiers on the back plane of the sectors results in a requirement for low power consumption since the proportional wire gain varies by approximately 3% for a 1°C increase in gas temperature. It also requires that the preamplifiers must be small so as to accommodate 1345 on a sector. Approximately 6 cm² is available per preamplifier to accommodate the preamplifier itself, cooling, interconnections and mechanical structures. To satisfy these requirements the design uses special components to achieve a low noise, low power (< 120 mW) preamplifier occupying 1.2 cm² of surface area. A current output is provided that drives 100 feet of 50 ohm ribbon coaxial cable connected to the remote amplifiers. The current drive was selected to minimize the effect of ground currents. Use of this technique gives ground signal rejection ratios of 2000:1 at 60 Hz and 100:1 at 1 MHz.

The charge sensitive preamplifier integrates the detector charge signal resulting in a step signal with a 5 μ s decay into the amplifier which performs shaping and amplification. For the reasons discussed later, the output pulse shape produced by the amplifier is roughly a Gaussian shape peaking at 250 ns when an infinitely short charge impulse is fed into the preamplifier input. The amplifier also contains both a pole-zero cancellation circuit to correct for the 5 μ s decay on the preamplifier signal and a correction circuit to reduce the effects of the slow signal components produced by the ion chamber as positive ions drift far away from the proportional wire. The amplifier output is sampled and stored at 100 ns intervals by the CCD analog shift register.⁴ The samples are preserved as they are shifted along the CCD structure. Sixteen amplifiers are mounted on a board and 16 such boards (256 channels) are accommodated in a bin. A control board is also included in the bin. This board includes the test pulse (TP) gating circuitry and a register control (RC) function; these are used to examine the performance of all channels under computer control. The CCD elements and drives are mounted eight per board (16 channels) in a separate bins from the analog electronics.

In normal operation of TPC the trigger system⁵ which uses prompt signals from a number of detectors, starts the TPC readout timing sequence when an interesting event is known to be present in TPC. The first part of the timing sequences records the track in the CCDs. The CCDs continue to be clocked at 10 MHz until the interesting data is near the last of the CCD buckets. The CCD clock frequency is then changed from 10 MHz to 20 KHz and the true chamber readout starts. From this point the CCD output voltage steps at 50 μ s intervals presenting successively about 300 samples of the analog information from the chamber to the digitizers (remember that each sample represents 100 ns of the original chamber drift information).



TPC ELECTRONIC BLOCK DIAGRAM

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Fig. 2. Block diagram of the TPC electronics.

On the digitizer board⁶ (16 channels) the first 40 μ s of the 50 μ s/sample that is available is used to perform a Wilkinson run-down ADC operation, at the end of which 16 registers contain the amplitude information from 16 channels. The remaining 10 μ s of the 50 μ s period are used to compress the data by retaining only the data from channels where the amplitude exceeds minimum values assigned for each channel. The minimum values are contained in computer loaded RAMs included in the digitizer channels. At the end of this 10 μ s period, the output RAM contains the compressed data ready for transfer to the readout system and the computer. The output from this RAM is read out during the first 40 μ s of the next digitizer cycle. The data compression is essential because the relevant data from all 17,000 channels must be transferred to remote memories during each 40 μ s digitizing interval. To accomplish this the 17,000 digitizer output channels are read out by 30 parallel readout channels each transmitting 28 bits (9 bits of amplitude information, 9 bits of CCD bucket position, 10 bits of address) parallel at a 4.2 MHz rate. This corresponds to a maximum instantaneous data rate of 3.5×10^9 bits per second. After all interesting CCD buckets have been digitized and transmitted to the memories, the trigger system interrupts the computer which reads the data corresponding to the event. Upon completion, the computers release the trigger for a new event.

A system as large and complicated as the TPC needs built-in testing and control functions under complete control of the computers. The test pulser/control unit provide this function. It is designed to isolate defects to the single card level in most cases. Switches and registers are also controlled by this unit. The event processing microprocessors shown in the figure have not yet been implemented. They are intended as preprocessors for the computers.

A very important consideration in a system of this size and complexity is the cost per channel of the system. Careful choice of components, automatic testing procedures and the use of mass production methods have resulted in a total cost of \$114.00 per channel for the system. If all costs (management, design, auxiliary systems such as the trigger system, interlocks, power supplies, airconditioning, etc.) are equally proportioned between all TPC channels (~ 25,000) the cost is \$280.00 per channel. Considering that this is the first very large low-noise system of this type we feel that this is a remarkable achievement.

Analog Signal Processing

While the considerations involved in the choice of shaping networks in the TPC amplifiers are in some ways similar to those involved in the high-resolution spectroscopy amplifiers used with semiconductor detectors, they must meet some added constraints not generally encountered:

i) The potential importance of "jet" events in the physics of high energy e^+e^- collisions means that the analog signal shaping must be designed to permit observation of two events on a single proportional wire (or pad) in less than 1 μ s. This restricts the width of the shaped pulse to about 0.5 μ s. Furthermore, remembering that the analog signal is sampled every 100 ns by the CCD, implies that only five (or so) samples are used to reproduce a signal. This is a desirably small number of samples from the point of view of the readout and computer system.

ii) The electron current pulse shape from the wire reflects the angle of the track with respect to the plane of the Frisch grid which shields the proportional chamber region from the main drift volume of the chambers. Thus, all electrons from a track segment parallel to this plane will arrive at the wire at the same time neglecting the effects of longitudinal diffusion. The resultant pulse current shape from the wire is the same as that due to a single primary electron. More generally, a track at an angle to the Frisch grid plane will produce a total current signal at the wire which is the sum of a series of sequentially-delayed single electron responses.

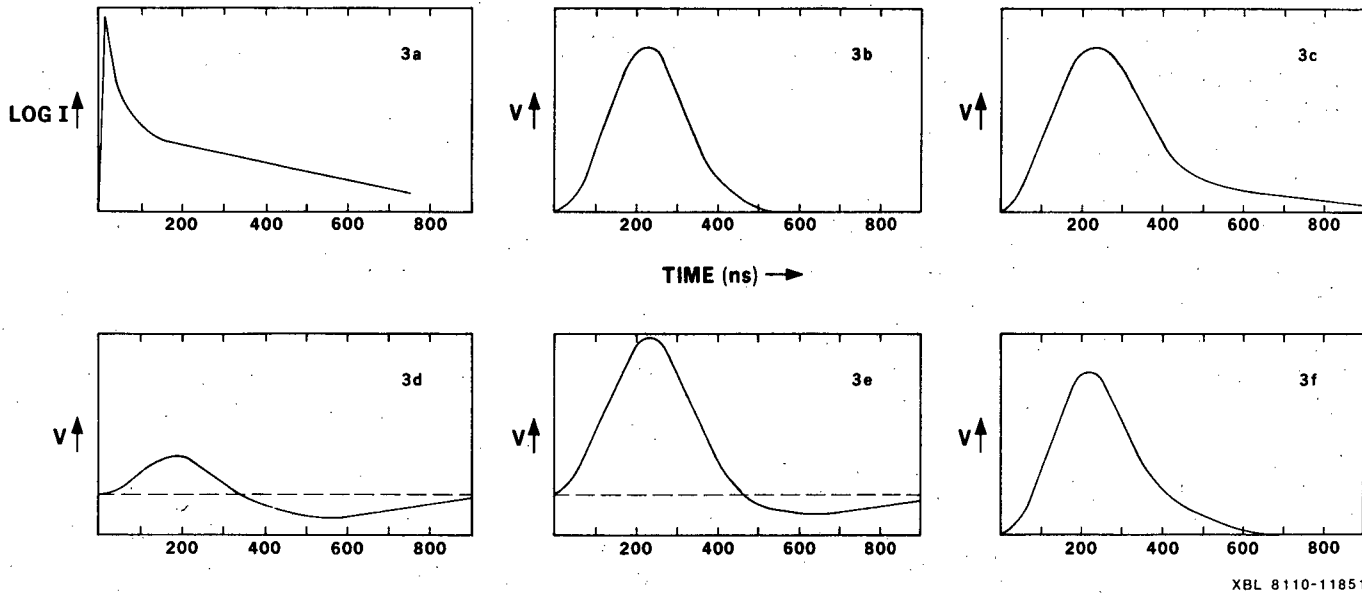
The single electron current pulse shape from the wire is shown in Fig. 3a. The rise time of this signal is less than 50 ns. For a track at an angle of 70° with respect to the plane of the Frisch grid, the total electron response for a 4 mm radial segment exhibits a rise time of 200 ns; tracks at smaller angles produce rise times ranging from 50 to 200 ns. Since the amplifier pulse shape is limited to a total width of about 0.5 μ s (a Gaussian shape peaking at about 250 ns), the variations in track orientation will result in considerable variations in the peak amplitude of signals at the output of the amplifier (due to so-called ballistic deficiency). It is obvious that the pulse area is much less sensitive to the detector current pulse rise time. Therefore, the total pulse area is calculated by the computer from the CCD sample. The fact that only samples exceeding a threshold (~ 5% of the typical signals) are read out clearly makes the area incorrect and it is essential to evaluate the errors caused by this effect.

iii) We note, in Fig. 3a, that a long tail exists in the current pulse at the proportional wire. The Townsend avalanche process produces most of its ionization very near to the proportional wire and the electrons from the avalanche are collected very quickly. Since they travel virtually no distance they produce almost no external current signal. The main signal derives from movement of the positive ions from the avalanche region. The fast rising portion of the signal is produced as the ions move in the very high field (near the wire) while the slow tail corresponds to the slow drift of the ions in the low electric field well away from the wire. For a true cylindrical proportional counter, the integrated charge signal S at time t due to a single electron is given by:⁷

$$S = (q/2 c \log(b/a)) \cdot \log(1 + 2 V_{out}/pa^2 \log(b/a)) \quad (1)$$

where a is the wire radius
 b is the radius of the outer cylinder
 c is the electrostatic capacity of the counter
 q is the charge on the electron
 V_0 is the applied voltage
 μ is the positive ion mobility
 p is the gas pressure

The signal shape shown in Fig. 3a, since it is the current signal, is a differentiated version of Eq. 1 with appropriate constants inserted. The long tail observed in Fig. 3c results in a significant pile-up problem in the analog signal processing channels. Therefore, a circuit method is used to partially compensate for the long tail. However, we note that the time variation of the signal (Eq. 1) involves a logarithmic term which cannot be modelled easily using normal RC circuit elements.



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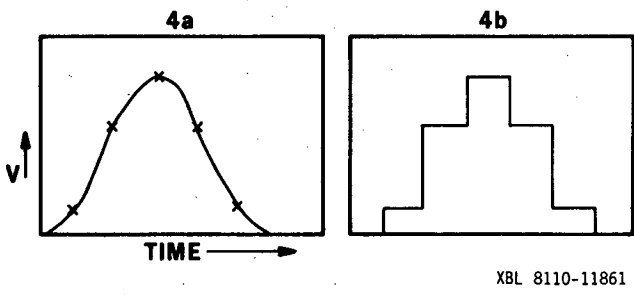
Fig. 3. Pulse shapes in the TPC analog system: a) Proportional wire current, b) Pseudo-Gaussian pulse, c) Amplifier output with no correction function, d) Amplifier correction function, e) Impulse response of the amplifier with correction function, and f) Amplifier out for input 3a with a correction function.

iv). The CCDs sample signals from the wires and the pads (after preamplifier/amplifier shaping and processing) at 100 ns intervals and the clocking operation cannot be synchronized with the signals arriving at the input. Therefore it is essential to consider the effects of the asynchronous sampling of signals roughly 0.5 μ s wide with samples every 100 ns. Since we must derive a best estimate of the area of the shaped pulse at the amplifier output and of the centroid time, it will be necessary to examine the effects of asynchronous sampling and the threshold imposed in the digitizer on these parameters.

The charge sensitive preamplifier integrates the current signal shown in Fig. 3a. Since the RC decay of the preamplifier output signal is pole-zero cancelled in the amplifier its effect can be neglected. The basic shape produced by the shaping network in the amplifier is close to that of a 5th-order Gaussian (i.e., 1 RC differentiator and 5 RC integrators all having the same time constant). Therefore, the response of the amplifier to a step function (or to a current impulse at the preamplifier input) is as shown in Fig. 3b. Since, at these short shaping times, the noise is almost entirely due to series or shot noise in the input FET, an improvement in noise performance could be achieved by using longer shaping times. However, the pulse pair resolution requirement (i) demands short shaping times and the noise performance (1000 electrons RMS for the wire channels with 20 pF capacity) is adequate to meet the requirements discussed earlier.

The effect of the slow component of the detector current pulse on a simple 5th-order Gaussian is shown in Fig. 3c; obviously the long tail is unacceptable due to its effect on following pulses. To improve the behavior, a small RC differential term (RC = 0.4 μ s) shown in Fig. 3d is added to the Gaussian response. This results in the step function amplifier response

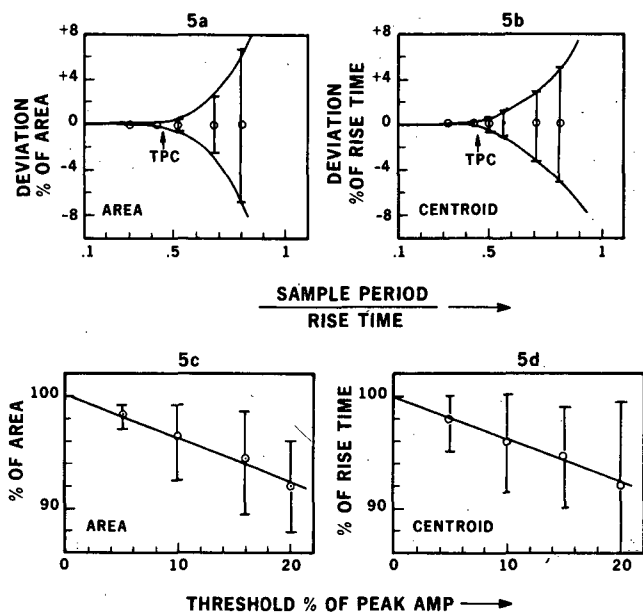
shown in Fig. 3e and the response shown in Fig. 3f for detector pulses. As stated earlier the logarithmic nature of the detector signal shape prohibits correct compensation of the tail; therefore a compromise has been made to achieve a return to the baseline that is within 4% of the signal for all times after 600 ns (on detector signals under the normal detector operating conditions).



XBL 8110-11861

Fig. 4. Pseudo-Gaussian pulse before and after CCD sampling.

The effects of the CCD sampling on the energy loss (dE/dx) and timing (i.e., axial position) information has been investigated by computer modelling. A typical signal at the output of the amplifier is shown in Fig. 4a and the CCD output is shown schematically in Fig. 4b. However, we note that the symmetry shown in Fig. 4b becomes considerably distorted when the sampling times shift in relation to the signal as they do in practice. The effect of such asynchronous sampling must also be evaluated in the model. The results of the modelling calculations are shown in Fig. 5.



XBL 8110-11863

Fig. 5. Variation of the pulse area and centroid (timing) after reconstruction of the CCD output. The error bars are the variation due to CCD phase. Deviation of area and pulse centroid are shown as a function of sample period divided by risetime (a,b) and the percentage decreases of area and timing as the threshold is raised at TPC operating parameters are shown in c and d.

The samples contained in the CCD are nearly instantaneous samples of the voltage at the input. Sampling theory shows that a signal instantaneously sampled at a frequency of twice the highest frequency of interest can be reconstructed with sinc functions in the time domain. For the TPC pulse shape a sampling frequency of approximately 6 MHz meets the requirement of sampling theory. The actual frequency used is 10 MHz. The modeling consisted of sampling the pulse shape at a fixed frequency. The phase of the CCD sampling clock was then shifted with respect to the signal. At each phase the areas and centroids of the resultant samples were calculated. Different periods for the sampling by the CCD clock were then selected and, for each sampling period, the phase was successively shifted. The results were then converted to percent deviation from the original amplifier output pulse area for the area and percent of the rise time (5% to peak) for the centroid.

Figure 5 a and b show the results where the error bars show the uncertainty due to the variations in the CCD sampling phase. The lines on the envelope of the error bars are added to guide the eye. It was found that a frequency of 10 MHz was suitable in the case of the TPC where the rise time is 220 ns. As noted previously, the CCD outputs are not read out if the digital equivalent does not exceed a predetermined threshold. This threshold is set at approximately four times RMS noise to minimize the number of words processed by the computer. This translates to a threshold of 3% to 5%.

To investigate the adverse effects of setting such a threshold, the program was changed to process only those samples that exceeded a threshold for the calculation of centroid and area. As the threshold was increased the value of both quantities decreased. The centroid moved to earlier times because the pulse fall

time is slower than the rise time (see Fig. 3f). The results are plotted in Fig. 5c and d for the ratio of sample period to rise time used in the TPC (0.45). The error bars are due to the variation of sampling phase and are quite sensitive to the fine details of pulse shape and phase. After computer correction for the systematic decreases the area and timing derived from the centroid are satisfactory up to a threshold of ~ 15%.

The calculation of the position of a track along a pad row uses the amplitude of samples at the same time in adjacent CCDs and is only sensitive if signals do not reach the threshold value. As stated, pad resolution is dominated by signal to noise ratios.

Recently a test was made using two sectors of the TPC located in a large pressure container. Cosmic rays were used to generate tracks. Thresholds were set at ~ 15%. The initial results are 220 μm pad resolution and 3.3% dE/dx resolution. Work is continuing on understanding the data and developing better software routines.

Acknowledgments

This work was carried out as part of the TPC project and with the close interest and involvement of the TPC physics team headed by D. Nygren. H. Hilke and D. Majka were particularly involved in the testing and measurement of proportional chambers and associated electronics. A number of people in our Department (Instrument Science and Engineering) contributed to the work of developing, fabricating and testing various parts of the analog electronics for TPC; these include M. Nakamura, S. Olson, K. Lee, T. Fujita, A. Jue, E. Shaw, F. Petro and T. Ortiz. N. Madden and M. Maier must be singled out as important contributors to the basic concepts involved in the system.

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