Presented at 1980 Nuclear
Science Symposium, Orlando,
Florida, 5-7 November 1980.

BNL 28660

CONF-801103--27

MASTER

SECOND COORDINATE READOUT IN DRIFT CHAMBERS BY TIMING OF THE ELECTROMAGNETIC WAVE PROPAGATING ALONG THE ANODE WIRE*

R. A. Boie, V. Radeka, P. Rehak, and D. M. Xi†

Brookhaven National Laboratory
Upton, New York 11973

November, 1980

*This research was supported by the U. S. Department of Energy: Contract No. DE-AC02-76CH00016.

†On leave from Institute of High Energy Physics, Academia Sinica, Beijing, The People's Republic of China.

SECOND COORDINATE READOUT IN DRIFT CHAMBERS BY TIMING OF THE ELECTROMAGNETIC WAVE PROPAGATING ALONG THE ANODE WIRE*

R. A. Boie, V. Radeka, P. Rehak, and D. M. Xi+

Brookhaven National Laboratory
Upton, New York 11973

Abstract

The feasibility of using an anode wire and surrounding electrodes in drift chambers as a transmission line for second coordinate readout has been studied. The method is based on propagation of the electromagnetic wave along the anode wire. The position of the avalanche along the anode wire is determined by measurement, in an optimized electronic readout system, of the time difference between the arrivals of the signal to the ends of the wire. The resolution obtained on long wires (~ 2 meters) is about 2 cm FWHM for minimum ionizing particles at a gas gain of $\approx 10^5$.

Introduction

Position measurement by determination of the electron drift time in a drift chamber appears to be the most practical way for charged particle momentum measurement in colliding beam experiments. The requirement on the position resolution in the direction of the magnetic deflection (usually azimuthal) is difficult to achieve by any other methods.

The problem arises in determining the second coordinate along the anode wire. The second coordinate is used to define the angle of the particle track and to establish the consistency of its recognition. Usually a lower position accuracy is sufficient for this direction.

Considerable effort has been put into the second coordinate readout. The known methods can be divided into two groups. The methods within the first group utilizes the signal induced on the cathode for the second coordinate measurement. The cathode strips[1] and delay lines parallel to the anode wire[2] are the methods most frequently used.

The cathode strips method presents well known ambiguity problems and therefore reconstruction difficulties for multiparticle events. The delay line parallel to the anode can limit the rate capability and its presence can interfere with the drift field requirements. Moreover, all methods within the first group require additional material within the drift chamber volume. This complicates considerably the mechanical construction of the chamber and introduces multiple scattering which may finally limit the precision of the momentum measurement.

The methods within the second group utilize the anode signal for the second coordinate readout and so do not require any additional material in the particle path. The position determination by charge division[3] and rise time[4] are "conventional" methods of the second group. Both methods require the resistive anode and give the constant relative error $\Delta l/l$ for a given signal charge. The rise time method depends critically on all parasitic capacitances and inductances in the chamber construction and connections of the wires to the preamplifiers which make the method less suitable for the application to the large drift chamber systems.

The purpose of this paper is to develop, study the performance, and the practical aspects of the second coordinate measurement by timing of the electromagnetic wave propagating along the anode wire (direct timing). The method belongs to the second group, i.e., uses the anode signal, and therefore does not complicate the mechanical construction of the chamber and does not require any additional material within the chamber.

The direct timing method measures the second coordinate by measuring the time difference between the signals arriving at each end of the anode wire. It can be viewed as a delay line readout method, where the anode plus surrounding electrodes are used as a transmission line. Since the method is based on time measurement, it is explicitly consistent with the drift time measurement. The resolution of the direct timing method, Δl, is expected to be largely independent of the length of the wire for a given signal charge, therefore this method should be preferable for large chamber systems.

Principle of the Method

The method uses the anode and the surrounding electrode(s) configuration as a delay line. Since the signal propagages with the speed of light along the wire, the timing accuracy and stability throughout the signal processing chain is required in a very short time scale (one centimeter of length corresponds to ≈ 67 picoseconds.)

The method requires identical fast preamplifiers, shaping amplifiers, and fast discriminators at each end of the wire. The time difference between the discriminator signals is the measure of the position along the wire.

Figure 1 illustrates the principle of the method. The preamplifier signals resulting from ^{55}Fe x-rays are shown. The upper trace of the oscilloscope picture displays the signal from one end of a 2.2 meter long wire, the lower trace displays the signal from the other end. The oscilloscope was triggered by the upper trace signal only. Relatively good timing (a narrow spread at one point) was achieved for the lower trace signal in spite of the wide distribution in the pulse height and the rise time. This is due to the fact that both amplifiers receive identical signals and only the relative timing enters into the position measurements. This "compensation effect" tends to relax some of the requirements on the discriminator performance.

Analysis of the Method

Direct timing is an extreme case of the delay line method of the position sensing. The delay line readout method has been studied previously.[5] The resolution is determined largely by the signal-to-noise ratio. The delay line is a nondissipative position sensing medium in principle. The noise in the line is generated in the terminations and in the amplifiers. To achieve the best resolution we have to: (1) terminate the line without

*This research was supported by the U. S. Department of Energy: Contract No. DE-AC02-76CH00016.

+On leave from Institute of High Energy Physics, Academia Sinica, Beijing, The People's Republic of China.

adding dissipative elements and (2) realize the optimum filter for timing.

The method for terminating transmission lines with "electronically cooled" preamplifiers was developed and its theory is described elsewhere.[5] In principle, the resistive termination is realized by a capacitance in a feedback of an integrating (charge) amplifier. (The circuitry of the "electronically cooled" preamplifier will be presented later.)

The existence of the optimum timing filter for gas proportional detectors represents a puzzling problem. A terminated transmission line is a resistive load to the preamplifier input so the noise is white. The optimum filter for timing is the derivative of the optimum filter for a amplitude measurement. The optimum filter for a amplitude measurement in the presence of white noise is a mirror image in time of the signal waveform at the preamplifier input. The convolution results in a bipolar response with maximum slope at the zero crossing, which leads to the well known antiwalk properties.

The variety of the signal waveform is the main reason that we could not apply optimum filtering to the direct timing method.

Two examples of the signal current waveform are shown in Fig. 2. The waveform for each ionizing particle is a superposition of the waveforms from the individual ionization clusters as they arrive at the anode. We could not find any suitable "average" waveform for which optimized signal processing improved timing for all waveforms compared with the timing of a simple leading edge discriminator. (The waveform at the input of the leading edge discriminator was, of course, filtered to limit the bandwidth of the system.)

The optimum filter for timing uses a priori knowledge of the signal waveform. The leading edge discriminator system, on the other hand, uses only the very first part of the signal waveform. We believe that the better performance of the leading edge discriminator technique is a quantitative confirmation of the large variety of the signal waveforms from gas proportional detectors. The only common feature for all signals is the fast rise time due to the first cluster. Because we are interested only in the time difference, the "compensation effect" for the leading edge method is an adequate substitution for the antiwalk property of the optimum filtering. (The leading edge timing is also the timing used for the standard drift time measurement, so this convenience simplifies the design of the signal processing for a drift chamber system.)

The line termination in the frequencies of interest requires special attention. Any preamplifier, being a charge-sensitive device, has a capacitance at its input. A real amplifier has also the stray capacitance of the layout, etc. In our case, the total capacitance of the termination was about 8 pF. The capacitance of the termination corresponds to the capacitance of 1 m of the line, or at f = 160 MHz an impedance Z = 120Ω which is substantially smaller than the transmission line impedance Z_o = 360Ω.

The termination of the line is very important for the position measurement close to the line end. If the injected signal is so close to the A-end of the wire (for example) that the reflection from the A-end arrives to the B-end before the direct signal has reached the threshold value, the signal waveform at the B-end is distorted and the "compensation effect" is lost. This results in serious degradation of the position resolution close to the ends of the wire.

The line termination was improved (at the expense of the bandwidth) by inserting an inductance $L = Z_o^2 C$ between the end of the wire and the preamplifier (Z_o is the line impedance, C is the total capacitance of the termination). The insertion can be viewed as a new element of the delay line, which continues the delay line with the same impedance. Figure 3(a) shows the schematic of the transmission line with a termination network at each end. The resistive termination was realized by a capacitor in feedback. The only noise source added is the preamplifier noise which is lumped into the voltage noise source e_n. Because of the feedback, the equivalent series noise voltage appears at the termination in series with the "cooled" termination resistance. Figure 3(b) shows an equivalent system for the noise analysis. The real amplifier with feedback was replaced by an ideal noiseless amplifier with zero input impedance, noiseless termination Z_o, and noise source e_n in series. There is also an additional noise as a consequence of the wire resistivity. For simplicity, the noise connected with the dissipation in the wire was lumped into two noise sources e_{LW} and e_{RW} at the left and the right end of the wire.

The filtering, due to the circuitry following the preamplifier (not shown in Fig. 3), can be described by a simple transfer function in the Laplace domain $U(s)_{\text{shaping out}}/I(s)_{\text{preamp in}} = A/(1+sT_F)$, where A is a constant describing the gain of the system and T_F integration time constant.

The detail noise analysis is straightforward but cumbersome. Here we will give only results of the analysis for a special case where the filtering time constant T_F is equal to τ,

$$T_F = \tau = Z_o C \ ,$$

where Z_o is the line impedance and C is the total capacitance at the termination. Normalizing to the pulse injection into the delay line, the equivalent noise charge, for example, at the left end of the wire can be written,

$$(ENC)_L = \left[\exp\left(\frac{\tau}{2}\right)\right] \sqrt{\frac{C}{Z_o}\left(\frac{9}{30}\,\overline{e_{LA}^2} + \frac{3}{80}\,\overline{e_{TW}^2} + \frac{1}{32}\,\overline{e_{RA}^2}\right)} \ . \tag{1}$$

where $\overline{e_{LA}^2} = 4kTR_s$ is the noise power density of the preamplifier itself;

$\overline{e_{RA}^2} = 4kTR_s$ is the noise power density of the preamplifier at the other end;

$\overline{e_{TW}^2} = \overline{e_{LW}^2} + \overline{e_{RW}^2} = 4kTR_W$ is the noise power density of the wire (R_W is wire resistance).

For the leading edge timing method, the time spread is given as,

$$\sigma_{t(RMS),L} \doteq \frac{ENC}{Q_s \cdot SLOPE}$$

$$\doteq C^{3/2} \cdot Z^{\frac{1}{2}}\, \frac{\left[\exp\left(\frac{\tau}{2}\right)\right] \cdot \sqrt{\frac{9}{80}\,\overline{e_{LA}^2} + \frac{3}{80}\,\overline{e_{TW}^2} + \frac{1}{32}\,\overline{e_{RA}^2}}}{0.91\, Q_s} \tag{2}$$

where SLOPE $\doteq 0.91/\tau$ is the slope of the signal at the discriminating input due to the delta pulse injected into the wire; Q_s is the signal charge used for timing, that is, the charge arriving within time $\approx \tau$. The position resolution is determined by the timing error from the two ends. Due to the presence of L and C at the line termination, the noise at each end is dominated by the noise coming from its own preamplifier, so the noise from two ends are practically uncorrelated.

Thus,

$$\sigma_\ell = \frac{c_L}{2} \cdot \sqrt{2} \cdot \sigma_t \simeq C^{3/2}/Q_s \quad , \qquad (3)$$

where c_L is the speed of light. We would like to stress that Q_s is only a small part of the total signal charge. As was already mentioned, the direct timing uses only the "first cluster" arriving to the wire. Q_s is a portion of the charge due to the "first cluster". As is known,[5] the charge as a function of time for a point ionization in a cylindrical field is given by

$$Q(t) = \frac{Q_T}{\ln\left(1+\left(\frac{b}{a}\right)^2\right)} \cdot \ln(1+t/t_o) \quad t \leq t_o \left(\frac{b}{a}\right)^2 , \qquad (4)$$

where a is wire (anode) radius

b is the cathode radius

$$t_o = \frac{a^2 \ln(b/a)}{2\mu_p V_o}$$

μ_p is the mobility of the positive ions

V_o is the voltage between the electrodes

Q_T is the total amplified charge.

For a practical case $t_o = \tau = 3\text{ns}$,

$$Q_s(t=t_o) \doteq Q_T \times \frac{\ln 2}{\ln 700} \doteq Q_T/10 \quad . \qquad (5)$$

In principle, each ionization cluster along the particle track contains position information as to where the particle track is along the wire. If the signal from all the clusters for each particle could be used in the measurement of the second coordinate a better position resolution could be achieved at a lower gas gain.

We have studied the feasibility of the readout system which uses more than the first cluster for the measurement of the second coordinate. After observing about 100 waveforms on the storage oscilloscope, we have concluded that an improvement of about a factor ~ 1.5 as compared with the first cluster method can be achieved. The main reason for such a small improvement is the diffusion of the primary ionization from position inside the chamber further away from the wire. The diffusion degrades the rise time of the signal which makes them less valuable for the direct timing method.

Preamplifier

The diagram of the preamplifier with a cooled termination is shown in Fig. 4. It is a faster version of the preamplifier previously described.[5] Special attention was paid (1) to keeping the input capacitance as low as practical and (2) using all transistors with such bias current that f_T of each transistor is at least 2 GHz. Because the resistive termination by capacitance feedback integrates the input current, there is a differentiation with a time constant T_F between two stages of the amplifier.

The response of the preamplifier to the calibration pulse injected between the inductance and the first transistor of the amplifier is shown in Fig. 5(a). The calculated response (for a special case $T_F = \tau$) has a form $V = e^{-t/\tau} \cdot [(1-\cos(t/\tau))]$ which closely fits the observed waveform.

The noise performance of the open input configuration was also tested. The pulse response in this case is $V \simeq Z_o\, t/\tau \cdot e^{-t/\tau}$, and keeping the notation of the previous section we can write

$$\text{ENC} = \frac{e}{2\sqrt{2}} \cdot \frac{\sqrt{\tau}}{Z_o} \cdot \sqrt{\overline{e_n^2}} \quad . \qquad (6)$$

The measured value of ENC was about 1100 electrons which agrees well with an expected value of equivalent series noise resistance of 60Ω. (≈ 10% excess of the noise.)

Figure 5 shows the pulse response of the common base input preamplifier.[7] With this configuration, the input capacitance problems are greatly reduced, so no inductance is needed and the pulse response is faster. Unfortunately, to terminate the line we need a physical resistor and the noise of the resistor more than cancels the merit of a faster response. The measured position resolution of the common base termination is about 60% worse than the resolution achieved with the cooled termination for the same signal charge.

Results

The properties of the readout were studied with an experimental cylindrical detector as a model of a single cell of a drift chamber with the following parameters: length ℓ = 217 cm, anode diameter 25 and 50 μ (anode wire resistance 220 and 57Ω), cathode diameter 17 mm, gas 82% Ar, 10% CH_4, and 8% methylal.

The schematic diagram of the setup used for the measurement is shown in Fig. 6. The preamplifier at each end of the wire was followed by an ORTEC AN 302/NL-amplifier and Chronetics model 151 discriminator. The time differences were measured by an ORTEC 467 TAC followed by a multichannel analyzer. An electron from ^{90}Sr penetrates the chamber and triggers the scintillation counter. The chamber signal propagates along the anode wire. The signal from one end starts and the signal from the other end, after a suitable delay, stops the time-to-amplitude converter. The number of triggers in the scintillation counter as well as the number of coincidences from both ends of the chamber, plus the scintillation counter, were scaled to measure the efficiency of the method. During the test, the gas gain and the discriminator threshold were kept at such a level that the efficiency was at least 98%.

As expected, the readout is linear, that is, the position is a linear function of the time difference. The pulse height analyzer displays of the measured position resolution with the linear and logarithmic vertical scales are shown in Fig. 7. The measurement was taken with a 50 μ wire and the gas gain 9 x 10^4 (charge integrated for 2 μs). The peaks are not Gaussian and are broader towards the wire ends. Figure 8 shows the resolution as a function of the position along the wire for the different values of the inductance in the series with the line termination. Figure 8(a) shows the full width at half maximum. Figure 8(b) shows the full width at one tenth of the maximum. The results are almost independent of the inductance at the middle of the chamber, but close to the chamber end and the best resolution was measured with 1 μH inductance. ($L_{Theory} = Z_0^2 C = (350\Omega)^2 \cdot 8pF \doteq 1\ \mu H$.)

The loss of the resolution near the wide end is due to an imperfect line termination as previously mentioned. A reflected signal arrives to the far end of the wire with an inversion of the polarity. The effect of its combination with the direct signal is to delay the trigger from the discriminator. The increased delay puts the measured position further away from the center. If particles pass close to the chamber end, the resolution has a tail which is outside the chamber. We can use information about the physical length of the chamber to improve the position resolution near the end. The dotted lines in Fig. 8(b) show the maximum possible error (expressed as full width at tenth maximum) if the ionization is assumed to be inside the chamber.

Let us compare the measured results with the limits of the resolution due to the noise. Substituting into relation (1) $Z_0 = 350\Omega$, $C = 8$ pF, $R_W = 57\Omega$ and $R_s = 60\Omega$, we obtain ENC of 2000 electrons (measured value 2400 electrons). Assuming the mean "first cluster size"[8] of 12 electrons, at the gas gain 9×10^4, the Q_s according to relation (5) is 11×10^4 electrons which gives $\Delta\ell_{RMS} =$ 1.2 cm which is in good agreement with the measured value. The measured distribution is not a Gaussian, so the simple relation between FWHM and RMS values does not exist.

The resolution obtained with 25μ W gold plated wire was about the same as the quoted resolution obtained with 50μ wire of the same material. The smaller diameter wire adds more noise to the system due to its higher resistance. On the other hand, the time development of the signal charge is faster on the smaller wire due to the smaller value of the t_0 constant as follows from relation (4). For the same gas gain, a chamber with 25μ wire delivers larger signal charge Q_s for the measurement than a chamber with a 50μ wire. The signal increase compensates for the higher noise in the system.

The attenuation of the signal along the wire was not a problem. In a first approximation, the attenuation lowers the amplitude of the signal arriving to the wire end linearly with the distance traveled. This attenuation causes a delay in the discriminator triggering which is also proportional to the distance traveled by the signal. The overall effect, in a first approximation, is just a slight decrease of the apparent velocity of the signal propagation along the wire.

It is interesting to compare the direct timing and charge division methods. The charge division method gives the relative error, which depends on the total avalanche size,

$$\left(\frac{\Delta\ell}{\ell}\right)_{FWHM} = \frac{k}{Q_T(pC)} \quad . \qquad (7)$$

The constant k depends on the details of the filtering, but for a practical system has almost a universal value of .5%.[9]

The precision of the direct timing method in the case of a small line dispersion is independent of the wire length and depends only on the charge of the "first cluster". (Relation [3])

Combining relations (7) and (3), we can find a length of the wire for which both methods give the same position resolution.

$$\ell_{EQ} \doteq 250\ W_g \quad , \qquad (8)$$

where W_g is the gap width (cathode-cathode distance) of the chamber or the length of the ionization track within the chamber for more complicated chamber geometries.

If a system under consideration has the wire longer than ℓ_{EQ}, direct timing can be preferable to the charge division (for $W_g = 1$ cm, $\ell_{EQ} = 2.5$ m).

Conclusions

The feasibility of the second coordinate measurement in drift chambers by timing of the electromagnetic wave propagating along the anode wire was demonstrated. For the gas gain typically used in the proportional chambers the position resolution is largely limited by the electronic noise. Certain deterioration of the position resolution closer to the end of the chamber is connected with the imperfect line termination due to the input capacitance of the preamplifier. This input capacitance also degrades the noise performance, therefore limiting the position resolution.

In the limit of a small line dispersion, the position resolution of the direct timing method is independent of the wire length. As is known, the charge division method gives a constant relative error $\Delta\ell/\ell$. A formula for a critical wire length above which the direct timing can give the better resolution than the charge division method was found.

The rate capabilities of both methods are limited by the physics of the ionization and the drift of the electrons in the gases of the drift chamber.

The motivating discussions with R. Palmer about the use of the method and with J. Fischer and A. H. Walenta about the processes of the ionization and drift in gases are gratefully acknowledged.

References

1. E. Gatti, A. Longerie, and H. Okuno, Nucl. Instr. & Meth. 163 (1979) 83.

2. R. Grove, I. Ko, B. Leskovar, and V. Perez-Mendez, Nucl. Instr. & Meth. 99 (1970) 381. D. M. Lee, S. E. Sobottka, and H. A. Thiessen, Nucl. Instr. & Meth. 104 (1972) 179. J. R. Gilland and J. G. Emming, Nucl. Instr. & Meth. 104 (1972) 241. R. Bosshard, R. L. Chase, J. Fischer, S. Iwata, and V. Radeka, IEEE Trans. Nuc. Sci. NS-22 (1975) 2053. H. Okuno, R. L. Chase, J. Fischer, and A. H. Walenta, IEEE Trans. Nuc. Sci. NS-24 (1977) 213-217. M. Atac, R. Bosshard, S. Erhan, and P. Schlein, IEEE Trans. Nuc. Sci. NS-24 (1977) 195-199. C. L. Morris, H. A. Thiessen, and G. W. Hoffmann, IEEE Trans. Nuc. Sci. NS-25 (1978) 141.

3. J. L. Alberi and V. Radeka, IEEE Trans. Nuc. Sci. NS-23 (1976) 251. V. Radeka and P. Rehak, IEEE Trans. Nuc. Sci. NS-25 (1978) 46. V. Radeka and P. Rehak, IEEE Trans. Nuc. Sci. NS-26 (1979) 225.

4. R. B. Owen and M. C. Awcock, IEEE Trans. Nuc. Sci. NS-15 (1968) 290. A. Doehring, S. Kalbitzer, and W. Melzer, Nucl. Instr. & Meth 59 (1968) 40. C. J. Borkowski and M. K. Kopp, IEEE Trans. Nuc. Sci. NS-17 (1970) 340. C. J. Borkowski and M. K. Kopp, IEEE Trans. Nuc. Sci. NS-19 (1972) 161. C. J. Borkowski and M. K. Kopp, Rev. Sci. Instr. 46 (1975) 951.

References - (cont'd.)

4. H. Thyssen, N. Shenhav, H. P. Eulenberg, and A. Arbel, Nucl. Instr. & Meth. 165 (1979) 265.

5. V. Radeka, IEEE Trans. Nuc. Sci. NS-21 (1974) 51.

6. G. R. Richer, Jr. and J. J. Gomez, Rev. Sci. Instr. 49 (1969) 227.

7. R. A. Boie, A. T. Hrisoho, and P. Rehak, "Signal Shaping and Tail Cancellation for Gas Proportional Detectors at High Counting Rates", submitted to these Proceedings.

8. If a track passed ≈ 5 mm from the anode wire, the ionization from the closest 2 mm arrives at the anode within ≈ 2 ns. Taking the mean ionization density ≈ 60 electrons/cm, we obtain the "first cluster" size.

9. V. Radeka and P. Rehak, IEEE Trans. Nuc. Sci. NS-25 (1978) 46.

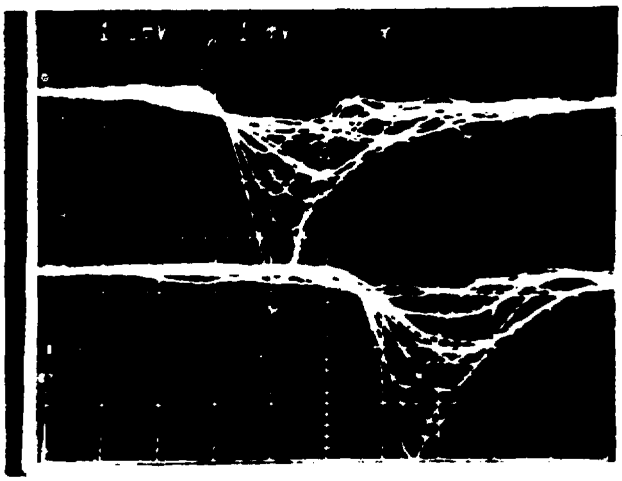
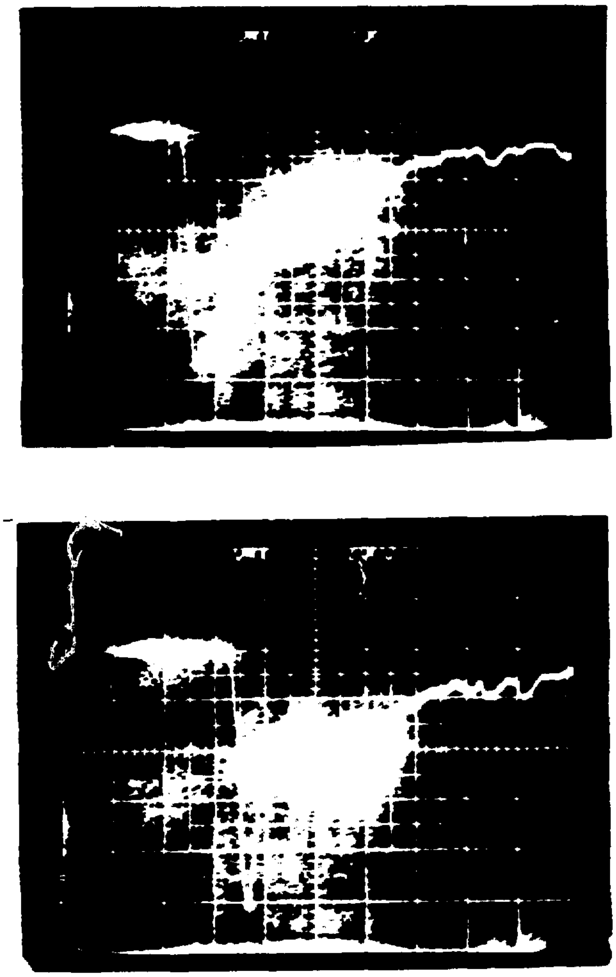


Fig. 1. Signal due to a ^{55}Fe x-ray from the preamplifiers at both ends of the chamber. Fast oscilloscope (Tektronix 7104) was triggered by the upper trace only. We can see that a good timing can be achieved on the lower trace in spite of the wide distribution of the pulse height and rise time.



Figs. 2(a),2(b). Signal waveforms at the output of the preamplifier for two samples of minimum ionizing particles.

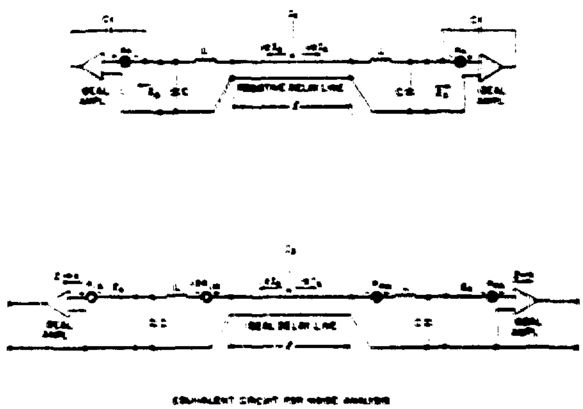


Fig. 3. Schematics of the anode surrounding electrodes configuration as a delay line for the analysis of the direct timing method. (a) Real resistive delay line and a feedback termination; (b) equivalent configuration.

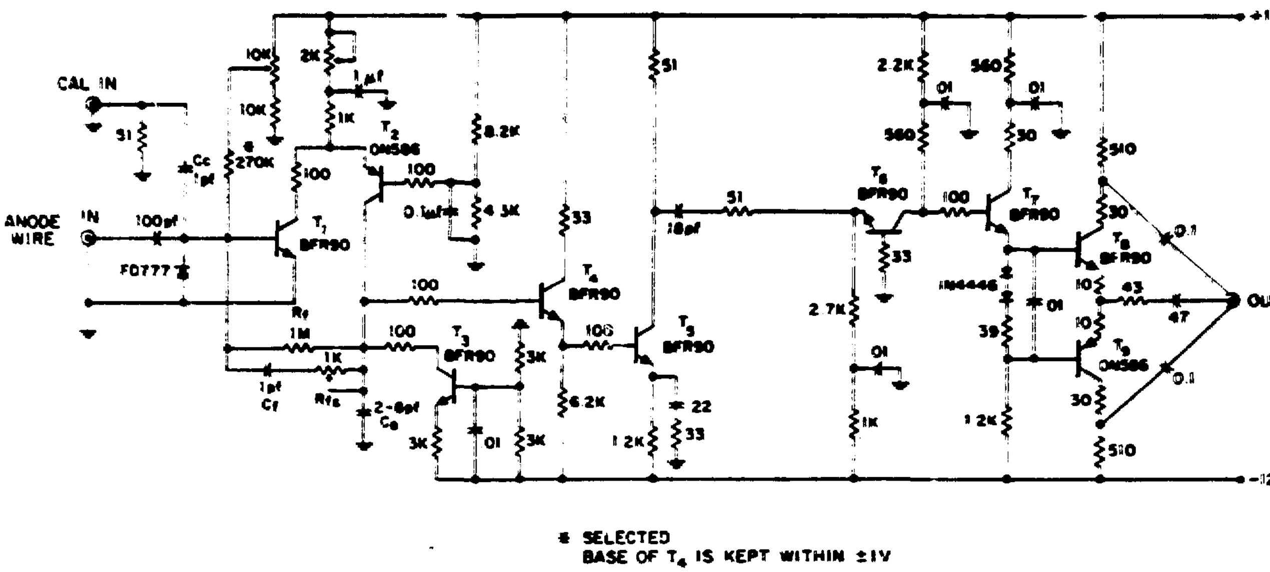


Fig. 4. Preamplifier for cooled termination. Special effort was made to keep the input capacitance as low as practical and to use all transistors with $f_T > 2$ GHz. Differentiation between two stages of the preamplifier cancels the integration effect of the first stage.

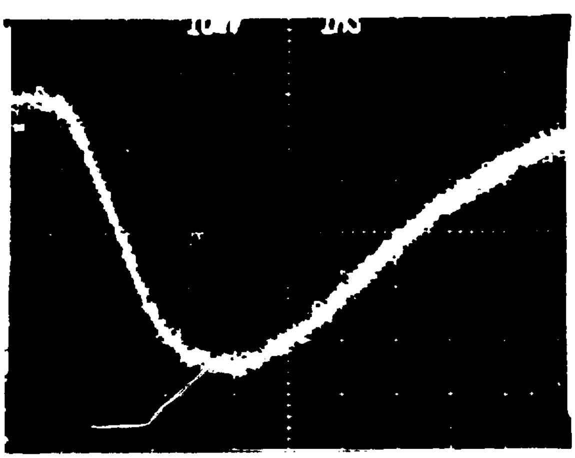


Fig. 5(a). Pulse response of the preamplifier with cooled termination. Calculated waveform $\approx e^{-t/\tau}[(1-\cos(t/\tau)]$, $\tau \approx 3$ ns.

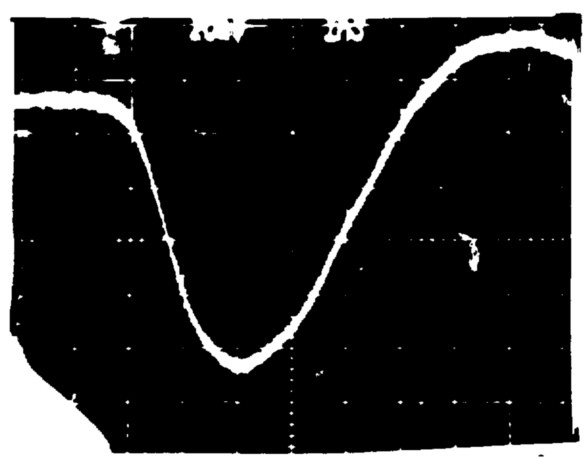


Fig. 5(b). Pulse response of the common base amplifier. Theoretical waveform $e^{-t/\tau} \cdot \sin(t/\tau)$.

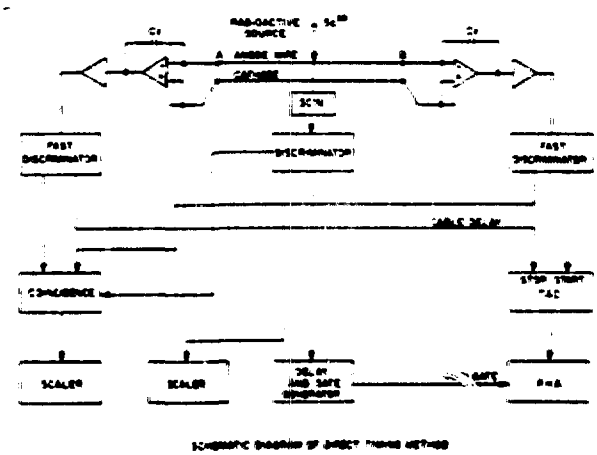


Fig. 6.

The setup used for studying the direct timing method. With the exception of the preamplifier, only commercial units were used. Two scalers were used to check the efficiency of the method.

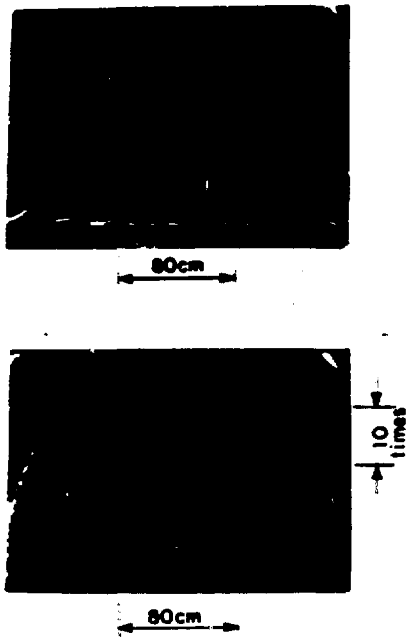


Fig. 7. Pulse height analyzer display of the position measurement with the ^{90}Sr source placed at different positions along the wire. Upper part, linear display; lower part, logarithmic display. Note a nonGaussian character of the peaks.

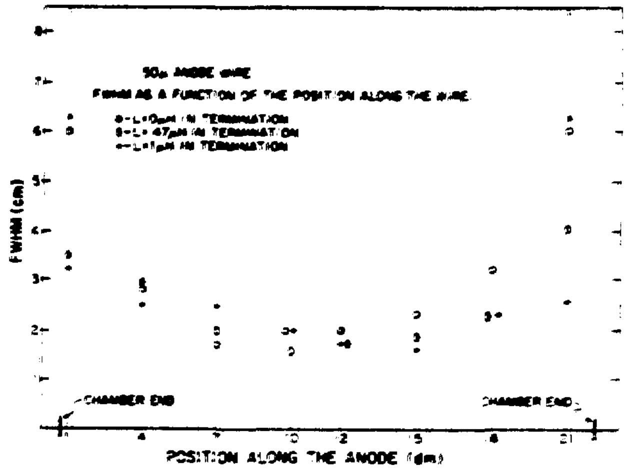


Fig. 8(a). Full width at half maximum (FWHM) as a function of the position along the wire for the direct timing method.

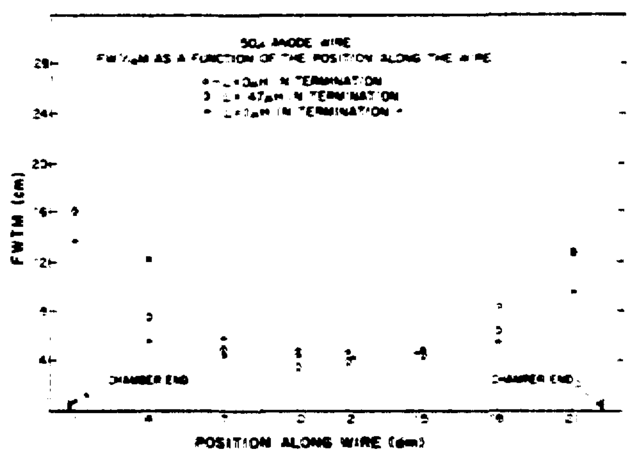


Fig. 8(b). Full width at tenth of maximum (FWTM) as a function of the position along the wire. Dashed lines represent the maximum possible error close to the end of the wire following from the constraint that the particle passed within the chamber.