GEM TN-93-303

T_0 and P_T Stand Alone Trigger in a Muon System Based on Drift Tubes

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February 1, 1993

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SUMMARY.

We describe an option for the time and momentum muon trigger based on drift tubes only. Simulation, experimental data and electronics analysis prove that the scheme is viable (reliable and well within the cost budget).

1. The Idea.

The idea of a stand alone trigger is to measure p_T of a track in the muon system and to assign this trigger to a single bunch crossing (i.e. to measure T_0 with an accuracy better than 16 ns) using drift tubes only. This information is assumed to be obtained at the level 1 trigger, i.e. faster than 1μs including drift time.

The p_T-trigger itself is not any different from any other proposed system (RPC's or CSC's). Segmentation (1 inch tube diameter) seems to be adequate (only Yes-No information is assumed) and maximum drift time of 300 ns does not make any constrain (the very forward region ($\theta \sim 9\text{-}15^0$) might require a smaller tube diameter (~1cm)). Calculations of the bending are trivial (fig.1a) and cannot take longer than 100-200 ns. However, drift time of 300 ns is definitely too long for straight forward timing. It is a measurement of T_0 that is the main issue.

The concept of T_0-measurement comes from an old idea as shown in fig.2. One can see that drift times measured in a pair of staggered cells do really provide information about T_0. However, one may notice that the reality is not so simple as presented in fig.2. First, drift time vs. distance, in general, is not a linear function. Secondly, the track can have a certain inclination (can be far not perpendicular to the chamber plane -- fig.3(a)). Third, as soon as the track is not perpendicular, it can go by the same side of two, rather than between wires -- fig.3(b). And last, δ-electrons and other time errors result in additional complications.

Does it mean that the idea of timing based on slow drift chambers is hopeless? The answer is *not at all.*

First of all, it turns out that function T(x) for typical gases can be rather reasonably approximated by linear plus parabolic terms (fig.4):

$$T(x) = a \cdot x + b \cdot x^2 \qquad (1)$$

Secondly, if one knew a track angle, it would make possible a simple calculation of T_0 (fig.5) as follows:

$$T_0 = \frac{T_1 + T_2}{2} - \frac{a}{2} C_\alpha - \frac{b}{4}\left(C_\alpha{}^2 + \frac{(T_1 - T_2)^2}{(a + bC_\alpha)} \right), \qquad \text{where } C_\alpha = R + \alpha D. \qquad (2)$$

where T_1 and T_2 are absolute times of signals measured in the two tubes, a and b are from eq.(1), R is a tube radius, D is a distance between tube layers.

Third, it is obvious that this expression gives the right answer only in a case when the track goes between wires. If it does not, the formula would give a rather arbitrary number.

These three assumptions gave an idea for a stand alone trigger:

1) One can see from fig.4 that formula (1) gives a very good approximation (difference between fit and data does not exceed ~ 4 ns in the worst points)*;

2) Inclination of a track in the chamber is the sum of an angle which an infinitely high momentum track would have (this is determined by a hit position within the chamber with an accuracy ~ 1 mrad) and an additional bending angle (which can be trivially obtained from comparison of hit positions in super layer SL2 and super layer SL3; in fact this angle is a measure of p_T which has to be measured any way -- fig.1 and Appendix 1);

3) If one would have calculated T_0's for each pair of tubes in a super layer, then the pairs where a track went between wires would give the right (and the same) number, whilst the other pairs would give rather random numbers which would be spread around with a very low chance of coincidence; thus, by picking up the most frequent answer one should get the right T_0 with a very high efficiency;

4) δ-electrons should also give random T_0's so that their influence on the T_0-trigger could turn out to be negligible for reasonable probabilities to get a δ-electron in a drift cell.

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* *It should be noted that the function T(x) could be any monatomic function when look-up tables are used for the calculations instead of a direct computation as given by formula (2). Therefore, the fact that we have assumed in this note* $T(x)=a*x+b*x^2$ *does not hurt the generality of the approach.*

Another way to do the same was proposed by L.Barabash [1]. One can see that any track is fully described by three parameters: T_0, a point of track entrance in a chamber, and a track angle. Therefore, one needs three equations to solve this. The idea was to use cell triplets to get these three equations. However, this can may not be so easy. First of all, due to left-right ambiguities each triplet gives four possible answers, just one of them being right. Then, the number of usable triplets (all three cells in row) per given number of layers is smaller than the number of possible pairs. And finally, the larger the number of planes participating in a single calculation is, the more distractible the effect of δ-electrons would be.

2. Monte Carlo.

In order to assess the efficiency of this proposed triggering scheme we have employed a Monte Carlo simulation. The middle super layer was assumed to consist of eight layers of axial tubes (N=8), all layers being in one chamber -- fig.6* . It is reasonable to restrict ourselves to the pairs of neighboring planes (N-1) and the pairs of planes with only one layer in between (N-2). The pairs separated far apart would give larger angle sensitivity in T_0-calculations, and, also, a constant C_α becomes angle dependent** . Thus, total number of pairs to be used in calculations 2N-3=13 (one can calculate that number of triplets is N-2=6).

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* *The results simulated for the case when these eight planes are grouped by four in two independent chambers can be found elsewhere [2]. The case of 6 axial planes, one pair of u- and one pair of v-planes has also been simulated [3]. All results are very similar.*

** *One can notice that the track can go by the different sides of wires in two ways: first wire - on the left, second - on the right; and otherwise - right/left. These two possibilities would give two different equations for T_0. However, if the distance between these cells is not big (one or two planes), one of the options corresponds to too big inclination and, therefore, is not of interest. When the two cells are far apart, both options are valid (in this case one option corresponds to a particular range of angles, whilst the other one corresponds to a different range of angles).*

First, we ran the MC without introducing any measurement errors and δ-electron production, to check how many pairs have a track going between wires. Fig.7 shows that, on average, there are about 8 good pairs (out of 13). These pairs give right answers. Also, one can see that wrong answers are spread apart so that a probability for a coincidence of two wrong answers should be very low. Table 1 shows that in the case of measurements without errors each event has at least 7 right answers.

To figure out the sensitivity of such a trigger to measurement errors, we put in the MC the following error sources:
1) δ-electron production (ε = probability to get a δ-electron per cell, δ-electrons are given a random distribution between 0 and the actual distance from a track to a wire). Typical probability is 3-5% as measured in our Fermilab tests [4].
2) δT, drift time error (jitter) due to diffusion, misalignment, electronics and etc. (2ns error is considered to be typical, which corresponds to about 100 μm space resolution).
3) ΔT, TDC bin width, the error which, essentially, could be included in the previous one.
3) $\delta\alpha$, an error in estimation of a track angle in the chamber (it is easy to estimate that if one uses only Yes-No information from tubes in SL2 and SL3 the error would be .003 rad (RMS) or smaller).

The MC was run with uniform angular spread of tracks within $-11^0<\varphi<+11^0$. A beam crossing number was assigned to each of 13 answers obtained for a track depending on the bucket (16 ns wide) the answer had dropped into. Then, the most frequent answer was considered to be THE final answer.

Tracks had no spread in θ so that no time correction on signal propagation along a wire was needed. It has been shown [5] that drift tubes have a very important advantage in terms of this correction since the z-coordinate is available from the same wires (by means of time difference from connected wire pairs) so that there is no need to correlate r_φ-measurements with independent z-measurements. The z-information is also necessary even for a p_T trigger in the end-caps [6].

At this first stage we also did not put multiple scattering into the MC. Nevertheless, it is shown (Appendix 2) that the multiple scattering does not lead to errors exceeding the typical measurement errors mentioned above and, therefore, can be neglected.

Applied separately, the errors result in trigger inefficiencies as presented in Fig.8(a,b,c). One can see that the typical errors (marked by arrows) are far away from dangerous boundaries where inefficiency drastically increases. Fig.9 shows inefficiency vs. muon momentum when all three errors are turned on. One can see that inefficiency remains very small even when all errors have been arbitrary doubled(!); also, a TDC bin width of 8 ns seems to be quite adequate (this is not surprising since this does not add much to already assumed time error of 4 ns (RMS)).

3. Experimental Data.

The results of the Monte Carlo simulation have been checked against the data obtained with the large scale LSDT prototype [7] during tests at TTR. The 4 m long prototype had 4 planes of tubes. It operated at limited streamer mode in a gas mixture Ar+Isobutane=1+3. The TTR trigger on a cosmic muon was not exactly correlated with the time at which the triggered muon went through. Thus, the drift chamber a priori did not have any T_0 information so that these tests have provided a very reliable comparison.

The analysis was done in the following way.

Some data cuts were made to insure that the chamber did really have a clean track at the level better than 1% (it is very important for inefficiency estimations).

First, a requirement of self-consistency of TTR data was applied (a reliable track and just one). These cuts are not essential for the discussion since at this step no information from the LSDT chamber had been used.

Secondly, some soft requirements were applied to assure the cleanliness of the chamber data:

-) the number of fired cells was required to be smaller than 7; this suppressed the rest of multitracks events which had not been caught at the stage of TTR cuts;

-) at least one hit per plane was required to suppress events where tracks went trough the edge of the chamber;

-) just one hit in the top plane was required to make sure that there is information about a coordinate along a wire (only this plane had wires connected in pairs).

No other cuts which would require any self-consistency of measurements in the chamber were applied.

After that an experimental function T(x) was fitted by a sum of linear and parabolic terms - fig.10.

Then, using external information (from TTR) about the angle of a track, all 6 T_0's were calculated (one can make 6 pairs out of 4 planes). Then, using TTR data (scintillators), the actual T_0 was calculated. The difference between these zero times is shown in fig.11. One can see that the majority of answers sit in zero and the peak is quite narrow ($\sigma \sim 3$ ns is mostly determined by the angle error).

After that, each of 6 answers was assigned to a particular 16 ns wide bucket and the bucket containing the largest number of answers was chosen as the final T_0-decision. Fig.12 shows the distribution of such decisions. One can see that the bucket "Zero" ('right' answer) has been selected in 94% of cases. About 5% gave wrong answers and less than 1% of cases (leftmost bucket) did not give any coincidence.

Then, we ran the MC for this 4 plane chamber. The following table (Table 2 in fig.13) compares the MC predictions and the data:

Four plane chamber:

	MC	DATA
Right answers	93.6%	94%
Wrong answers	6.1%	5%
No answer	0.3%	1%

The remarkable coincidence of data and simulation allows reliance on the MC results.

4. Is it necessary to know a bending angle?

When one thinks about this scheme a reasonable question emerges: how difficult is it to correlate hits in superlayer 2 and 3 to get a bending angle (which is needed for calculations)?

First of all, this has to be done anyway in any system to get a p_T trigger. Therefore, this is not a problem specific to the stand alone trigger.

The only worry one might have is a case when two actual tracks get close to each other. Let us assume that there are two tracks of relatively high momentum close to each other so that we could make several combinations between one of hits in the SL2 and two hits in the SL3. Also, let us assume that both combinations satisfy to the p_T trigger. Then, one might have a dilemma which of two possible bending angles to chose for T_0 calculations: two different angles could result in two different T_0-answers.

First, let us estimate if this problem is serious in the barrel. There are two components to be considered: accidental coincidence (when a track gets close to another one accidentally), and a correlated case (a decay of a high momentum Z^0 would be an example).

The simplest tactics could be as follows. As soon as one gets a track segment in SL3, it is projected back in the SL2. A track segment closest to this projected point is considered to be the right segment to be used for calculations of bending and T_0.

The distance between the projected point and the actual hit point in SL2 is (see fig.1(a))

$$\Delta Y = eB\frac{L_2(L_3 - L_2)}{2}\cdot\frac{1}{p_T} = \frac{3.6m}{p_T(GeV/c)} \tag{3}$$

Therefore, the probability to get an independent track within this distance (fig.14(a)) is

$$p = N\cdot(2\cdot\Delta Y\cdot L)\cdot T_{drift} \sim \frac{8.6\%}{p_T(GeV/c)} \tag{4}$$

where N = charged particle rate (~1. $cm^{-2}s^{-1}$ in SL2 @ 10^{34} luminosity [8]), T_{drift}~300 ns, L - drift tube length (~4 m). One can see that this probability is absolutely acceptable even for the lowest p_T~10 GeV/c.

Now let us consider a case of two correlated muons on an example of a Z^0 decay. If a Z^0 energy is E, then it decays into two muons with p_T~E/2 (in the barrel) and opening angle θ~2m/E~m/p_T. With this opening angle a distance between these two muons in the SL2 would be R~θ*L_2~m*L_2/p_T

which is considerably larger than ΔY. The probability to have these muons aligned so that in $r\varphi$-projection they would be closer than ΔY (fig.14(b)) is

$$p = \frac{(2 \cdot \Delta Y) / R}{\pi} \sim 0.4\% \tag{5}$$

which is again negligible (and does not depend on p_T).

Thus, these estimations show that there is no problem with a bending angle and <u>the T_0-trigger will, therefore, definitely work in the barrel</u>.

Before going to the end-cap regions where the rate will be much higher, let us take a look at what happens if information about bending is ignored. That means the angle to be used in calculations is determined by a track segment coordinate in SL2 alone (this is equivalent to an infinitely high momentum track). Fig.15 (we are still in the barrel) shows that if one would wish to have trigger for muons with p_T>30 GeV/c, this would work perfectly. However, it does not look satisfactory when the goal is 10 GeV/c.

Now when we go to the end-caps, the orientation of the drift tubes is different. In the barrel the bending angle is the angle of a track in a chamber. In the end-caps these angles are correlated, but are not the same (fig.16) and the angle of a track in a chamber is much more predictable (due to a large axial component of the muon momentum). At $\theta \sim 30^0$ the uncertainty in the angle of a muon going through the chamber is 2 times smaller than that in the barrel. In the very forward region the rate becomes very high and does not allow reliance on an unambiguous measuring of a bending angle. However, this is a region that does not need this measurement: the uncertainty does simply vanish. The efficiency of the T_0 trigger in the very forward chambers is shown in fig.17 (no information about bending angle has been used in T_0 calculations).

The conclusion is as follows:

BARREL: one needs to measure a bending angle and to use it in T_0 trigger and this does not seem to be difficult;

END-CAPS: the change of chamber orientation allows a full T_0 efficiency without measuring a bending angle which makes a T_0 trigger even simpler.

5. Time Budget for the Calculations.

The following very naive model is given with the purpose to show that even a very conservative estimation of the time needed to perform the calculations does not exceed 1 μs, including full drift time. More realistic (and simpler) electronics will be shown to do the same faster (~750 ns).

Table 3 shows that if one makes direct arithmetical calculations in three parallel streams (and assuming 50 ns per one operation), all T_0 answers would be obtained in 400 ns. About 100 ns should be enough to select the most frequent answer out of N~13. Adding 300 ns for full drift time, 50 ns for signal propagation along anode wires and 100 ns for bending angle estimation, one ends up with about 950 ns.

6. Electronics.

The possible realizations of the trigger electronics is attached in the Appendix 3. The general conclusion (R.Sumner [Appendix 3], D.Marlow [Appendix 4], M.Shaevitz [9], M.Atiya [9]) is that this electronics does not seem to be any difficult to build. It does not require anything not available today.

Since this trigger scheme does not require any special additional detectors, the cost of electronics represents the entire cost of the trigger. The trigger electronics has been costed to be about ~$21.4/channel (R.Sumner, LeCroy).

7. Background.

Charged particles.

As was estimated in a section 4, in the barrel the rate of punchthrough is low enough so that it results in an additional inefficiency not exceeding 1% @ $L=10^{34}$.

In the end-caps, there is no need to measure a bending angle of a track to calculate T_0. In this case an extra inefficiency would be determined by the probability of having two tracks very close to each other (within one tube) which is estimated to be around 1% @ $L=10^{34}$. As a consiquence, the T_0-trigger remains robust and becomes even simpler.

Neutrons.

Neutrons with a rate estimated to be 10^4 $cm^{-2}s^{-1}$ are equivalent to δ-electrons giving a small addition of about 1.5% (for a 4m long tube) to the probability ε to get a measurement spoiled by a δ-electron. The value of ε was conservatively estimated to be 5%. This would increase the T_0-trigger inefficiency by 0.2% (see fig.8a). If a neutron happens to get into a tube neighboring the tube containing a track, it can lead to an error in the reconstruction of the pattern to be used in T_0-calculations. This confusion is also effectively equivalent to a wrong time used in calculations, i.e. again equivalent to δ-electrons (additional $\varepsilon=1.5\%$).

Thus, neutrons themselves at a rate 10^4 $cm^{-2}s^{-1}$ result in ~.5% inefficiency of the T_0-trigger for 4 m long tubes. For shorter tubes, the contribution is proportionally smaller.

Also, should it be necessary, the neutrons can be easily sorted out on the base of z-coordinate correlation between planes in the chamber (this information is immediately available from time differences on the connected wires).

Electromagnetic debris.

Electromagnetic debris (electrons and photons) associated with a high energy muons can cause additional troubles for the T_0-trigger. Simulation for 1 TeV/c muons done by A.Ostapchuk [10] showed that this contribution could be well described by the binomial distribution with a probability to get a spoiled hit ~3.5%.

Thus, this could be again simply added to ε of δ-electrons.

The worst case.

The worst case would be a high energy muon @ $L=10^{34}$ with T_0 inefficiency not exceeding 3%: probability to get a spoiled hit is about 12% (5% δ-electrons, 1.5%+1.5% neutrons, 3.5% e/m debris) and this would give about 2% inefficiency; charged particle background would result in an additional 1% inefficiency.

8. Conclusions.

- **The Stand Alone Trigger proved to provide p_T and T_0 triggers.**

- **The experimental data validate the idea and the MC results.**

- **It has been shown that the decision can be easily made within the time range available at level 1 trigger (<1 μs).**

- **All information (p_T; T_0 and z (coordinate along a wire: axial in the Barrel and radial in End-Caps)) is available from the same end of a chamber, i.e. there is no problem inherent in the designs where this information has to be somehow correlated (e.g. time and z from wires, bending from strips).**

- **Electronics required is not primitive but not a state-of-the-art either. Electronics cost is estimated to be around $22/channel.**

9. Acknowledgments.

The author is very thankful to all who got involved in numerous and fruitful discussions of the concept: L.Barabash, C.Bromberg, G.Mitselmakher, L.Osborne, L.Rosenson, F.Taylor and many other members of the muon group. The expertise in electronics of R.Sumner and D.Marlow have played a crucial role in justifying the viability of the scheme and can not be overestimated. An in-depth look made by the external review committee (J.Branson, K.Foley, C.Fabjan) is appreciated very much. The critical overviews made by M.Atiya and M.Shaevitz were very important for a better understanding of the matters concerned and validating the concept.

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Figure Captions.

Fig.1(a). A muon track going through chambers of SL2 and SL3. The value ΔY is a measure of bending and, therefore, p_T.

Fig.1(b). A muon track in SL2: α_{02} is an angle which an infinitely high momentum muon would have; α_2 is an additional bending angle; $\alpha_{2TOT}=\alpha_{02}+\alpha_2$ is the angle of the track in the chamber.

Fig.2. The concept of T_0 calculations in a pair of staggered cells.

Fig.3(a). A track can be inclined.

Fig.3(b). An inclined track can go on the same side of two wires.

Fig.4. Fit of drift time data by a simple function $T(x)=a*x+b*x^2$:
(a) Ar+Isobutane=1+3;
(b) $CF_4+CO_2+C_4H_{10}$=70+20+10.

Fig.5. Calculation of T_0 in a pair of staggered cells when a track angle is known and the drift time function is $T(x)=a*x+b*x^2$.

Fig.6. Layout of drift tubes in SL2 used in the MC calculations.

Fig.7. Distribution of all calculated T_0's (13 T_0's per event). No measurement errors have been assumed.

Fig.8. Inefficiency of T_0-trigger when different sources of errors have been applied separately:
(a) inefficiency vs. probability per cell of getting a δ-electron;
(b) inefficiency vs. time error (RMS);
(c) inefficiency vs. angle error (RMS).

Fig.9. Inefficiency of T_0-trigger when different sources of errors have been applied together. Three numbers in the legend mean a δ-electron probability, time error (ns), angle error (mrad) correspondingly.
The first set of numbers represent typical values one might expect. Notice that the inefficiency is still small when all errors have been arbitrary doubled (the second set of numbers) and an additional error corresponding to a wide TDC bin width has been applied.

Fig.10. Fit of data (drift time vs. distance) obtained with the large scale

LSDT prototype at TTR by a simple function $T(x)=a*x+b*x^2$.

Fig.11. The difference between T_0 as calculated in the drift chamber and T_0 as measured at TTR (scintilators). All 6 T_0's per track are in the same histogram.

Fig.12. A distribution of *final* T_0-decisions. A bin width is 16 ns.

Fig.13. A four plane LSDT prototype and table 2 where cosmic muon results are compared with the MC simulation made for this chamber.

Fig.14(a). A scheme for calculation of probability that two independent tracks will get close enough to confuse the T_0 calculations (see text).

Fig.14(b). A scheme for calculation of a probability that two correlated muons ($Z^0 \rightarrow \mu,\mu$) will get close enough (in r_φ-projection) to confuse the T_0 calculations (see text).

Fig.15. A T_0-efficiency in the barrel when the information about a bending angle (α_2; fig.1(b)) is ignored.

Fig.16. The change of chamber orientation in the end-caps makes the track angle in a chamber be much more predictable than in the case of a track with the same p_T in the barrel.

Fig.17. A T_0-efficiency vs. muon p_T in the end-cap region for different θ <u>without</u> using any information from SL3 (δ-electrons (.05) and time error (2 ns) have been included).

Table 1

```
      ONE BUNCH (+-8 ns) WIDE BUCKET:
 a=   5.031063                    b=   1.411695
 KEY=1
 eps=.000    Terror(ns)=0.0    Tbin(ns)= 0.0    Aerror(rad)=.000

P= 10.GeV: Nyes-Nno-Nwrong-Nminus-Nplus= 100.00   0.00   0.00   0.00   0.00
P= 14.GeV: Nyes-Nno-Nwrong-Nminus-Nplus= 100.00   0.00   0.00   0.00   0.00
P= 20.GeV: Nyes-Nno-Nwrong-Nminus-Nplus= 100.00   0.00   0.00   0.00   0.00
P= 28.GeV: Nyes-Nno-Nwrong-Nminus-Nplus= 100.00   0.00   0.00   0.00   0.00
P= 40.GeV: Nyes-Nno-Nwrong-Nminus-Nplus= 100.00   0.00   0.00   0.00   0.00
P= 80.GeV: Nyes-Nno-Nwrong-Nminus-Nplus= 100.00   0.00   0.00   0.00   0.00
P=160.GeV: Nyes-Nno-Nwrong-Nminus-Nplus= 100.00   0.00   0.00   0.00   0.00
P=320.GeV: Nyes-Nno-Nwrong-Nminus-Nplus= 100.00   0.00   0.00   0.00   0.00
```

C.L.*	P=10	=14	=20	=28	=40	=80	=160	=320 GeV/c
0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	1859	1874	1875	1882	1902	1852	1904	1881
8	2386	2583	2724	3027	2873	2904	2975	2977
9	2219	2234	2220	2035	2193	2150	2100	2124
10	2240	2273	2276	2253	2260	2271	2186	2200
11	1101	884	725	627	585	619	605	585
12	92	65	81	84	87	76	69	60
13	103	87	99	92	100	128	161	173

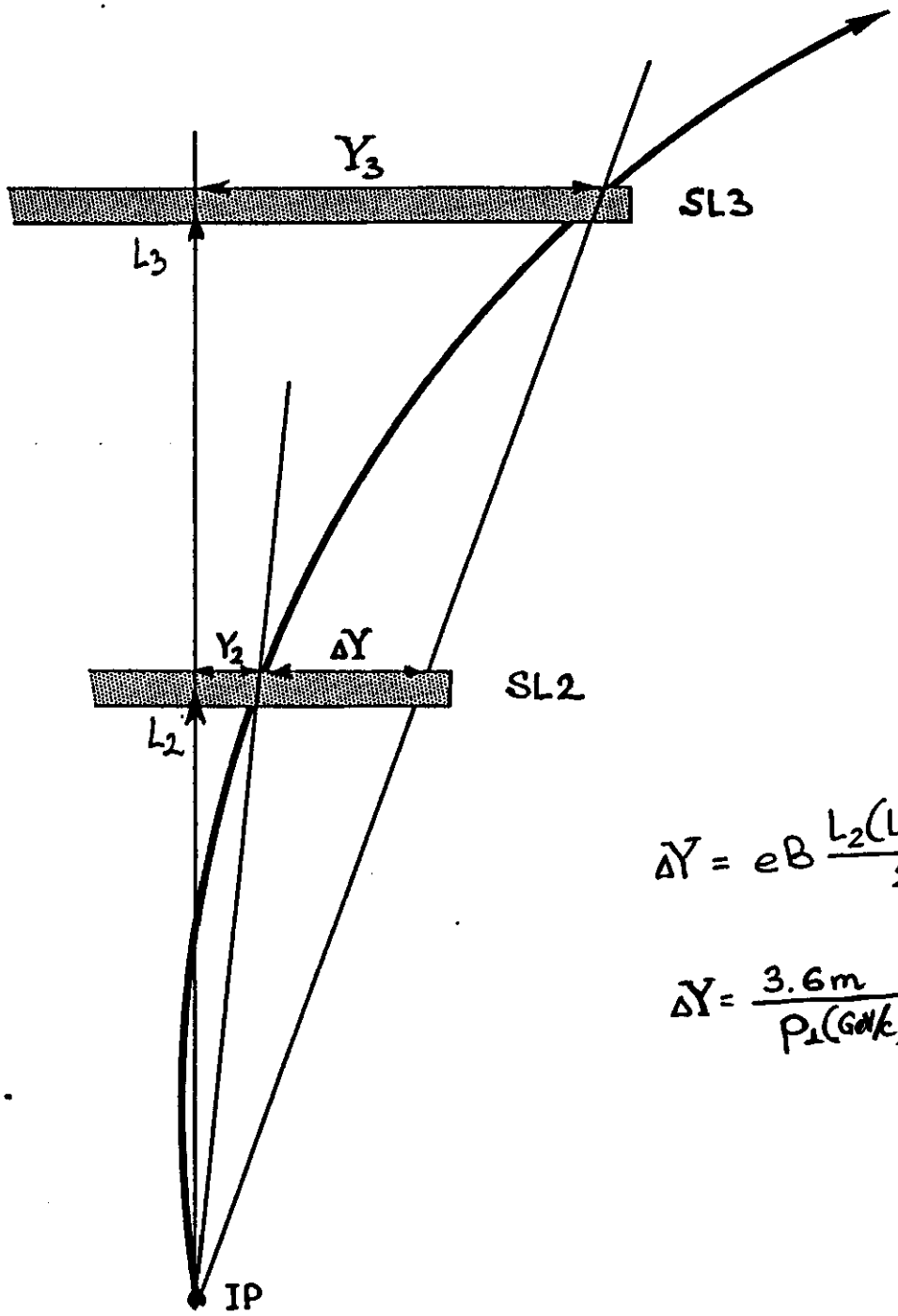
* C.L. – Coincidence level (number of right answers per event)

table 3

(INPUTS : T1, T2, α, a, b, C1, C2)

# 0 INPUT	X1 = T1	Y1 = T2	Z1 = α
# 1	X1 = X1 + Y1 (T_1+T_2)	Y1 = X1 − Y1 (T_1-T_2)	Z1 = Z1 · C2 (αC_2)
# 2	X1 = X1/2 $\left(\frac{T_1+T_2}{2}\right)$	Y1 = Y1 * Y1 $(T_1-T_2)^2$	Z1 = Z1 + C1 $(C_0=(C_1+\alpha C_2)$
# 3	X2 = a · Z1 $(a\cdot C_0)$	Y2 = Z1 * Z1 $(C_0)^2$	Z1 = b · Z1 $(b\cdot C_0)$
# 4	X2 = X2/2 $(\frac{a}{2}C_0)$	Y2 = b · Y2 (bC_0^2)	Z1 = a + Z1 $(a+bC_0)$
# 5	X1 = X1 − X2 $\left(\frac{T_1+T_2}{2}-\frac{a}{2}C_0\right)$	Y2 = Y2/4 $\left(\frac{b}{4}C_0^2\right)$	Z1 = Z1 * Z1 $(a+bC_0)^2$
# 6	X1 = X1 − Y2 $\left(\frac{T_1+T_2}{2}-\frac{a}{2}C_0-\frac{b}{4}C_0^2\right)$	Y2 = b/4 $(\frac{b}{4})$	Z1 = Y1/Z1 $(\Delta T^2/(a+bC_0)^2)$
# 7	—	—	Z1 = Z1 * Y2 $\frac{b}{4}(\Delta T^2/(a+bC_0)^2)$
# 8	X1 = X1 − Z1 (T_0)	—	—

$$T_0=\frac{T_1+T_2}{2}-\frac{a}{2}C_0-\frac{b}{4}\left(C_0^2+\frac{(T_1-T_2)^2}{(a+bC_0)^2}\right)$$



$$\Delta Y = eB\,\frac{L_2(L_3-L_2)}{2}\,\frac{1}{p_\perp}$$

$$\Delta Y = \frac{3.6\,m}{p_\perp(GeV/c)}$$

Fig. 1(a)

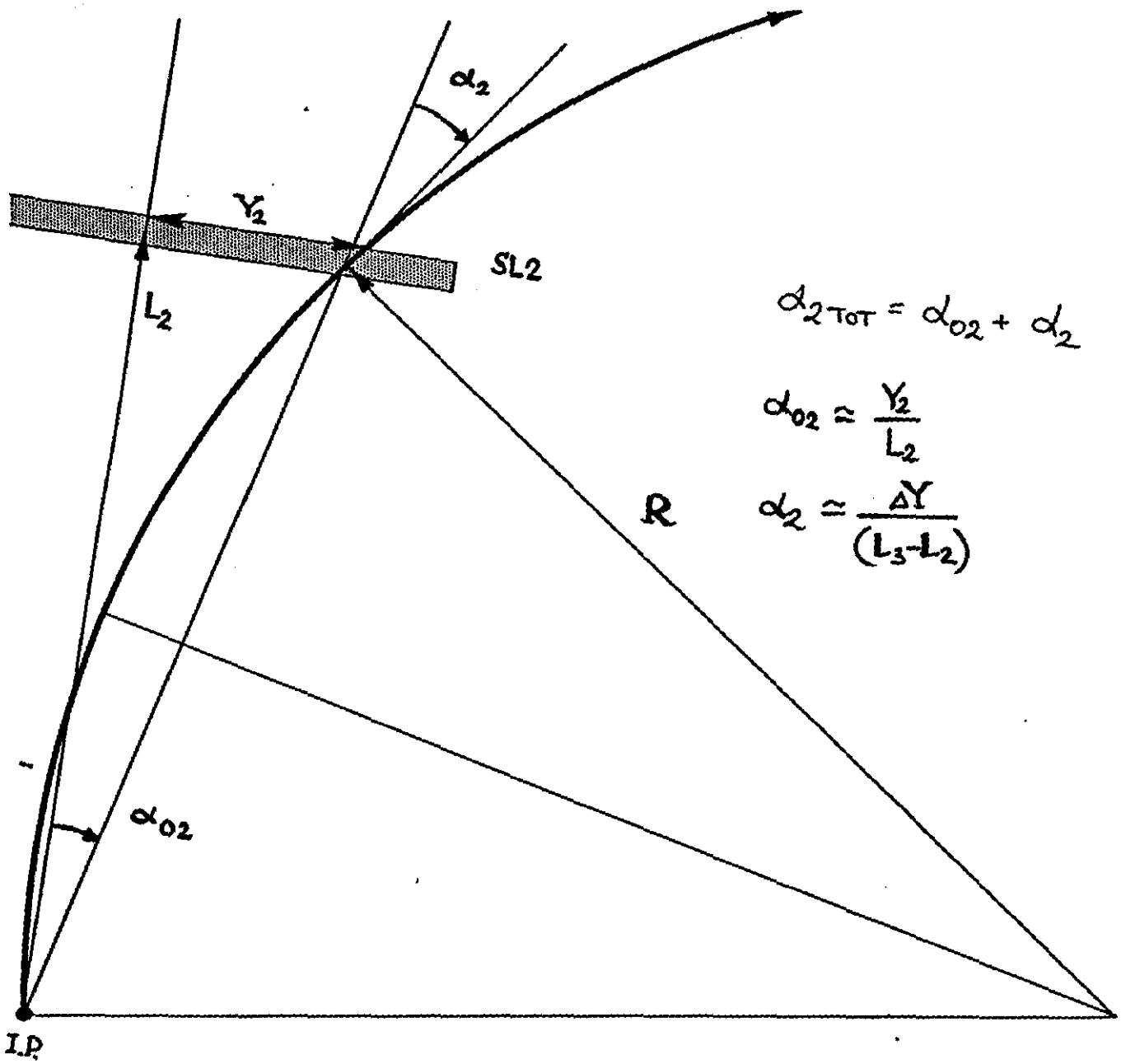
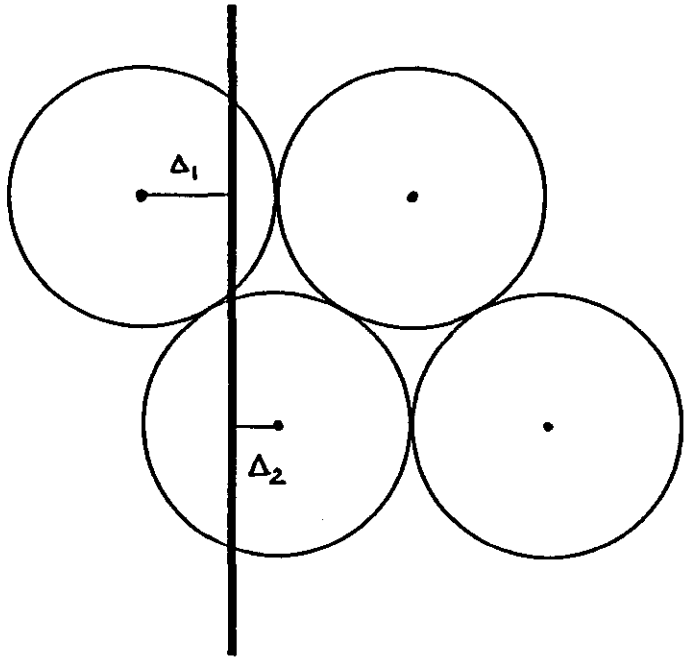

α_2
Y_2
SL2
L_2
$\alpha_{2TOT} = \alpha_{02} + \alpha_2$
$\alpha_{02} \simeq \frac{Y_2}{L_2}$
R
$\alpha_2 \simeq \frac{\Delta Y}{(L_3 - L_2)}$
α_{02}
I.P.

Fig. 1(b)



Drift Times:

$\tau_1 = \frac{\Delta_1}{V}$ $\qquad$ $\tau_1 = T_1 - T_0$

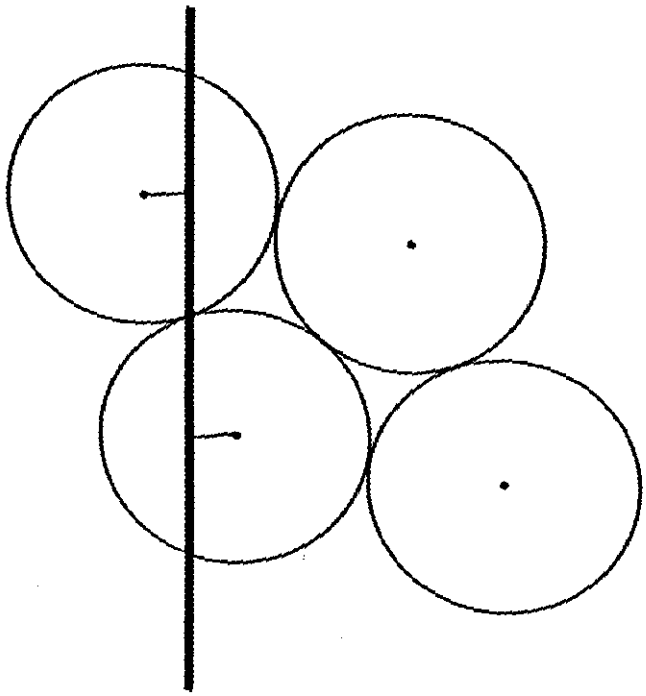
$\tau_2 = \frac{\Delta_2}{V}$ $\qquad$ $\tau_2 = T_2 - T_0$

$$\boxed{T_0 = \frac{T_1 + T_2}{2} - \frac{\Delta_1 + \Delta_2}{V}\,\frac{1}{2} = \frac{T_1 + T_2}{2} - \frac{T_{dr}}{2}}$$

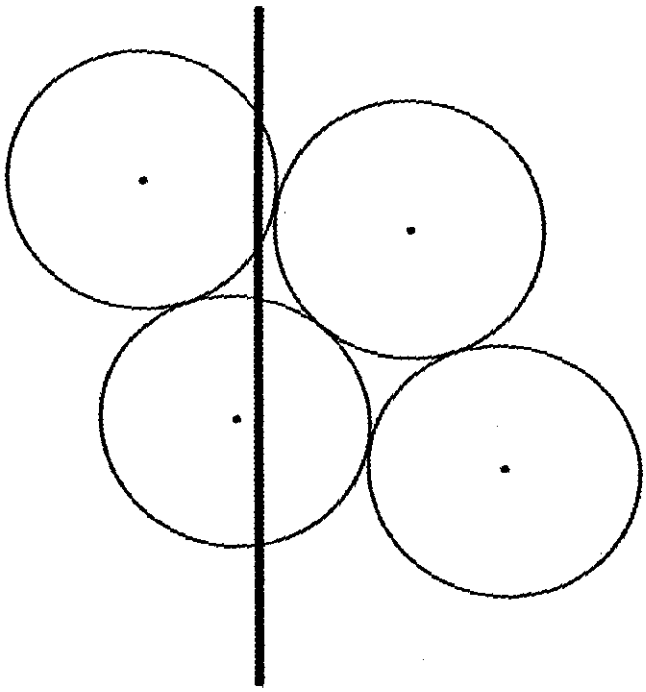
WHAT WAS USED:

1. V_{drift} = const
2. Vertical track ($\alpha = 0$) $\Rightarrow$ $\Delta_1 + \Delta_2 = R$
3. Track went between wires
4. Measurements are good (no δ-electrons, no background)

Fig. 2



(a)



(b)

Fig 3

y = m1*M0 + m2*M0*M0		
	Value	Error
m1	17.357073062	0.094725
m2	0.28546071821	0.0104131
Chisq	13.306709135	NA
R	0.99994534341	NA

T=a*X + b*X^2
(Points are calculated
from accurate fit of LASER DATA),
Ar+IB =25+75

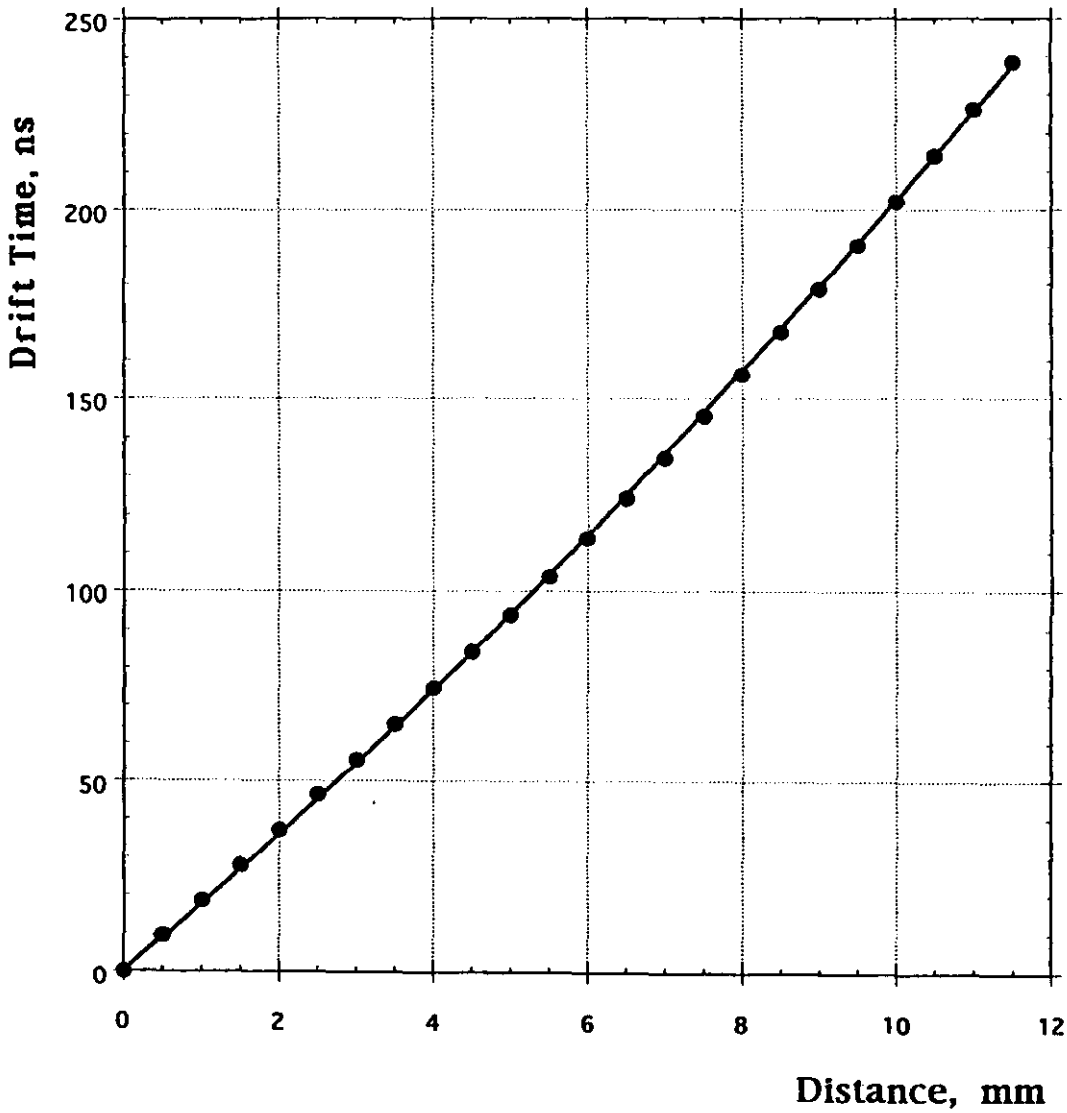


Fig. 4(a)

y = m1+m2*M0 + m3*M0*M0		
	Value	Error
m1	3.3417585497	0.484641
m2	5.031063318	0.23408
m3	1.4116950994	0.0239047
Chisq	2.9760939244	NA
R	0.99995388072	NA

$CF_4 + CO_2 + C_4H_{10} = 69 + 20 + 11$

U = 5.4 kV

Laser Data

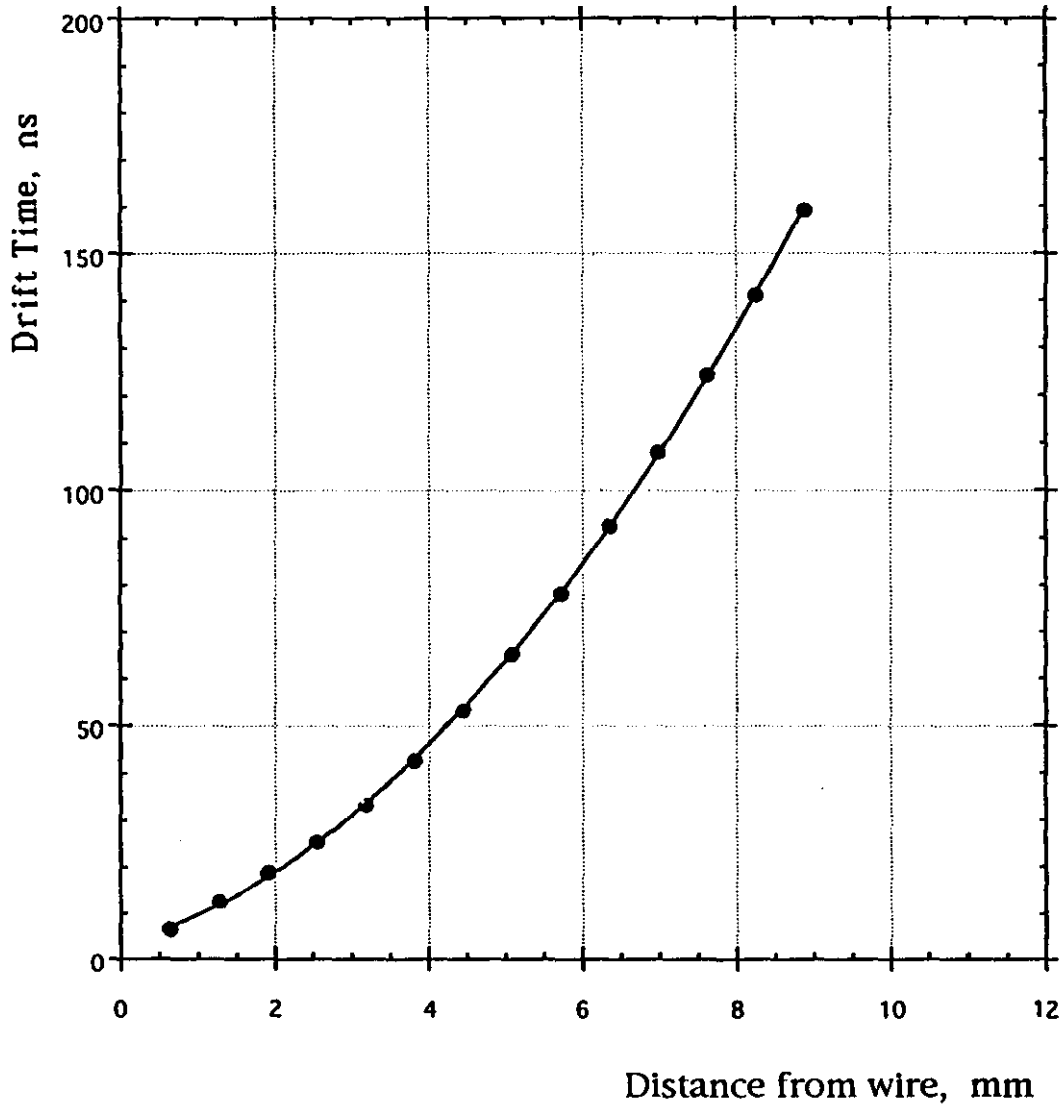
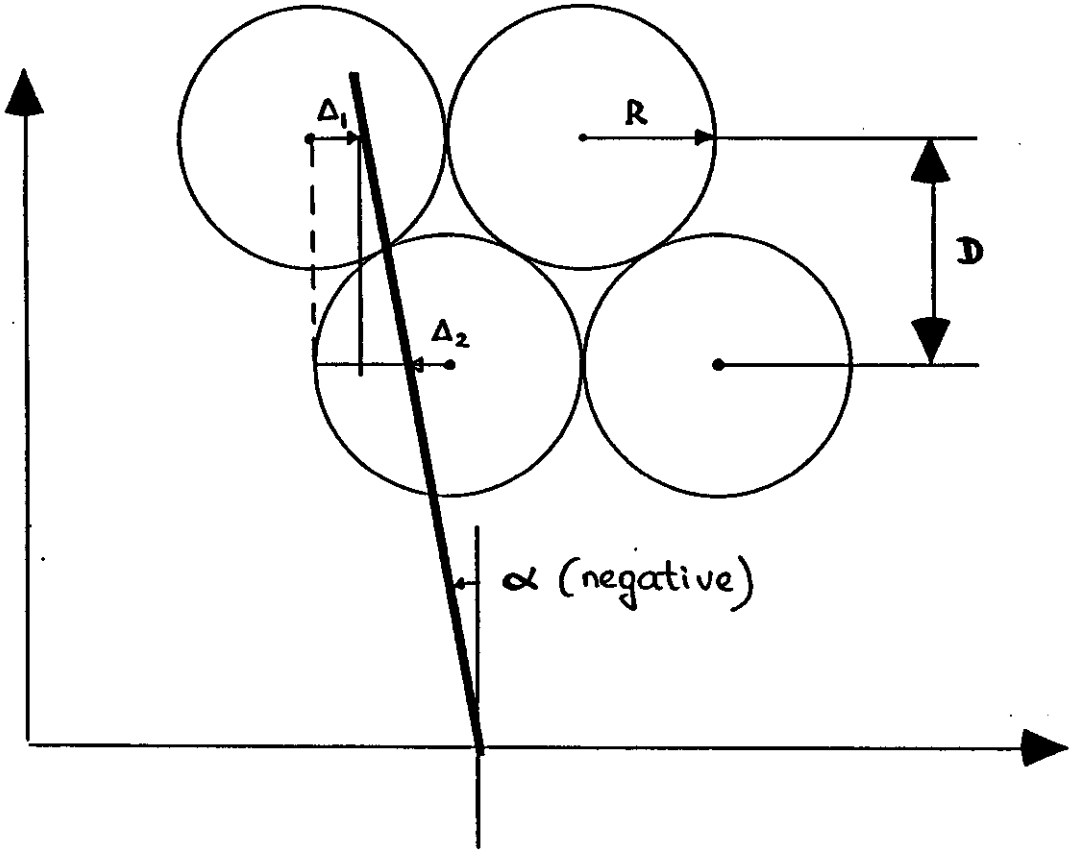


Fig.4(b)



Drift Times:

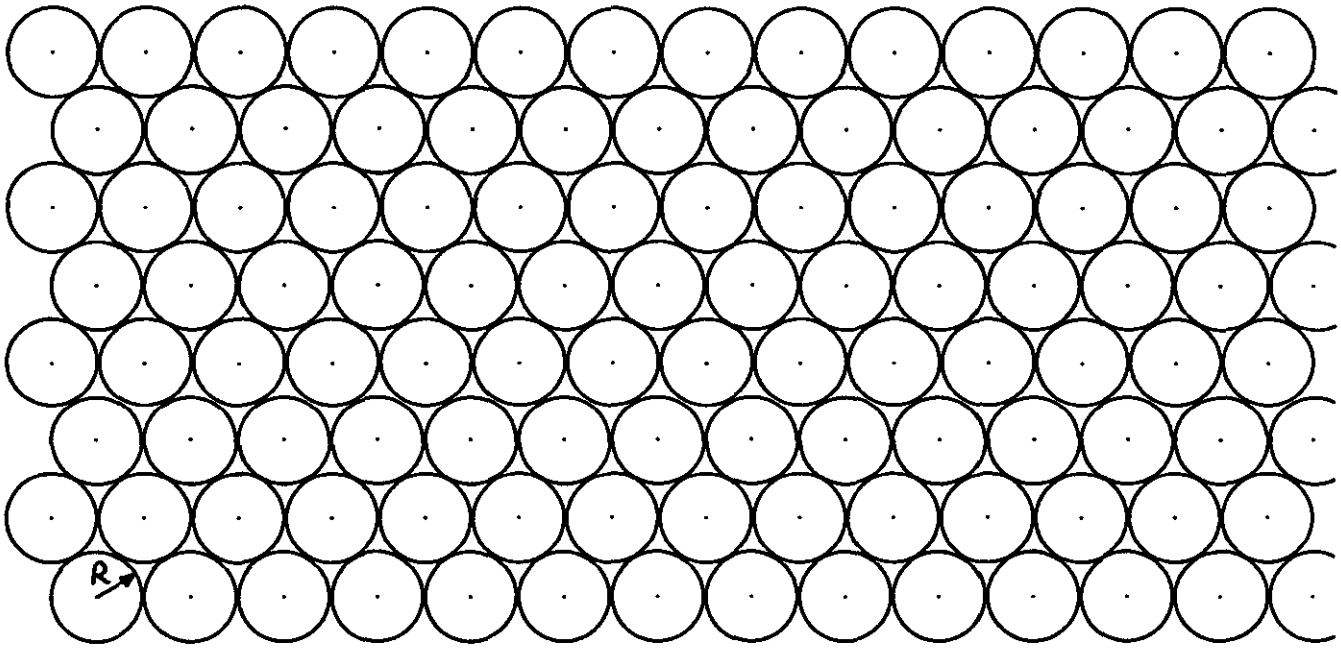
$$\tau_1 = a \cdot \Delta_1 + b \cdot \Delta_1^2 \qquad \tau_1 = T_1 - T_0$$

$$\tau_2 = a \cdot \Delta_2 + b \cdot \Delta_2^2 \qquad \tau_2 = T_2 - T_0$$

$$\Delta_2 = R + \alpha D - \Delta_1 = C_0 - \Delta_1$$

$$\boxed{\begin{gathered} T_0 = \frac{T_1 + T_2}{2} - \frac{a}{2} C_0 - \frac{b}{4}\left(C_0^2 + \frac{\Delta T^2}{(a + bC_0)^2}\right) \\ C_0 = R + \alpha D \end{gathered}}$$

Fig. 5.



R = 12.5 mm

Fig.6

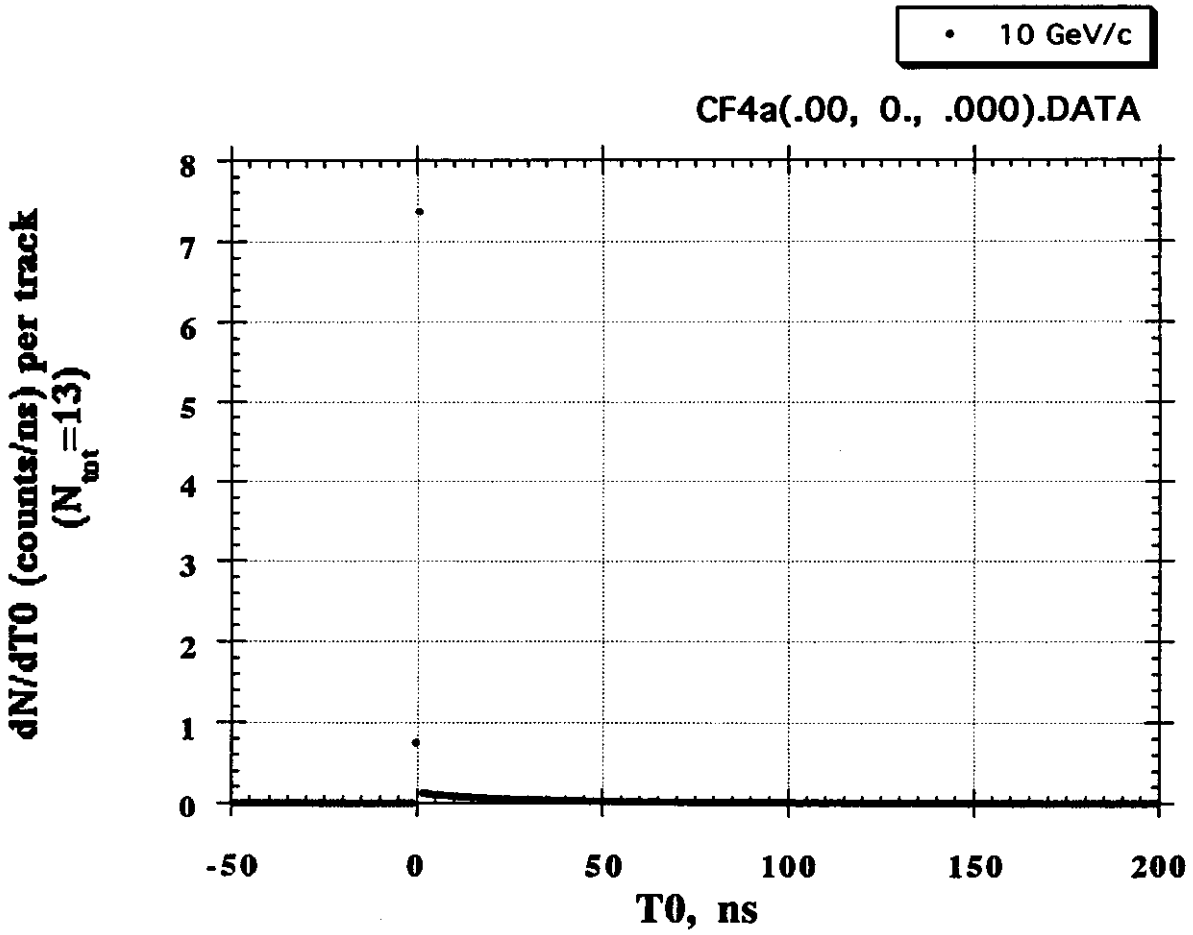
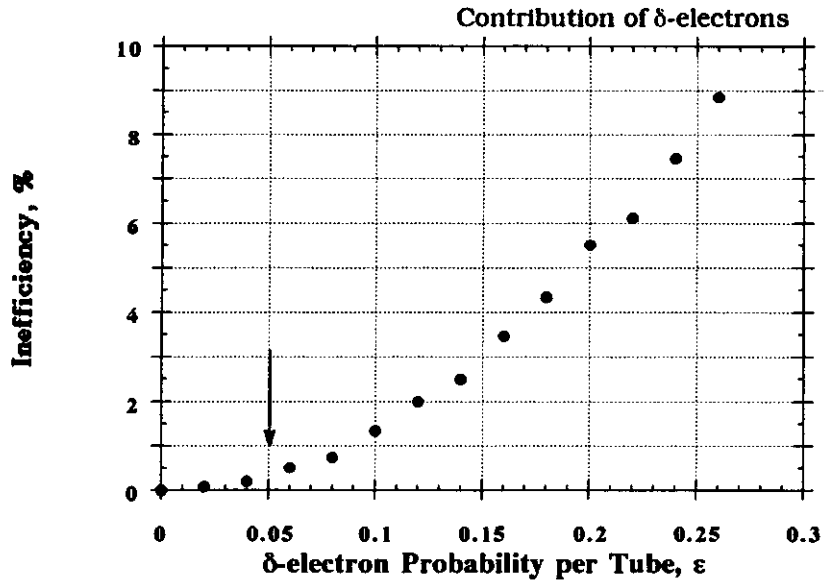
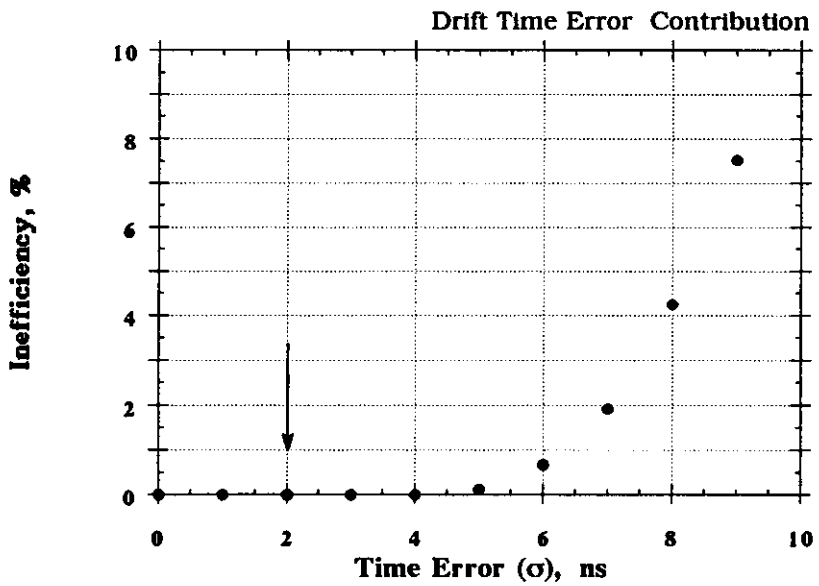

10 GeV/c
CF4a(.00, 0., .000).DATA
dN/dT0 (counts/ns) per track
(N_{tot}=13)
8
7
6
5
4
3
2
1
0
-50
0
50
100
150
200
T0, ns

Fig. 7


Contribution of δ-electrons
Inefficiency, %
0
2
4
6
8
10
0
0.05
0.1
0.15
0.2
0.25
0.3
δ-electron Probability per Tube, ε


Drift Time Error Contribution
Inefficiency, %
0
2
4
6
8
10
0
2
4
6
8
10
Time Error (σ), ns

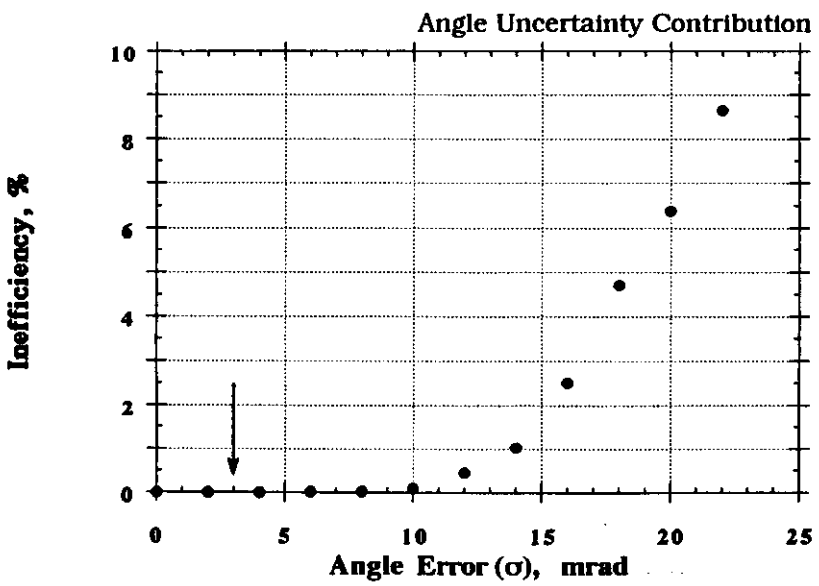

Angle Uncertainty Contribution
Inefficiency, %
0
2
4
6
8
10
0
5
10
15
20
25
Angle Error (σ), mrad

Fig. 8.

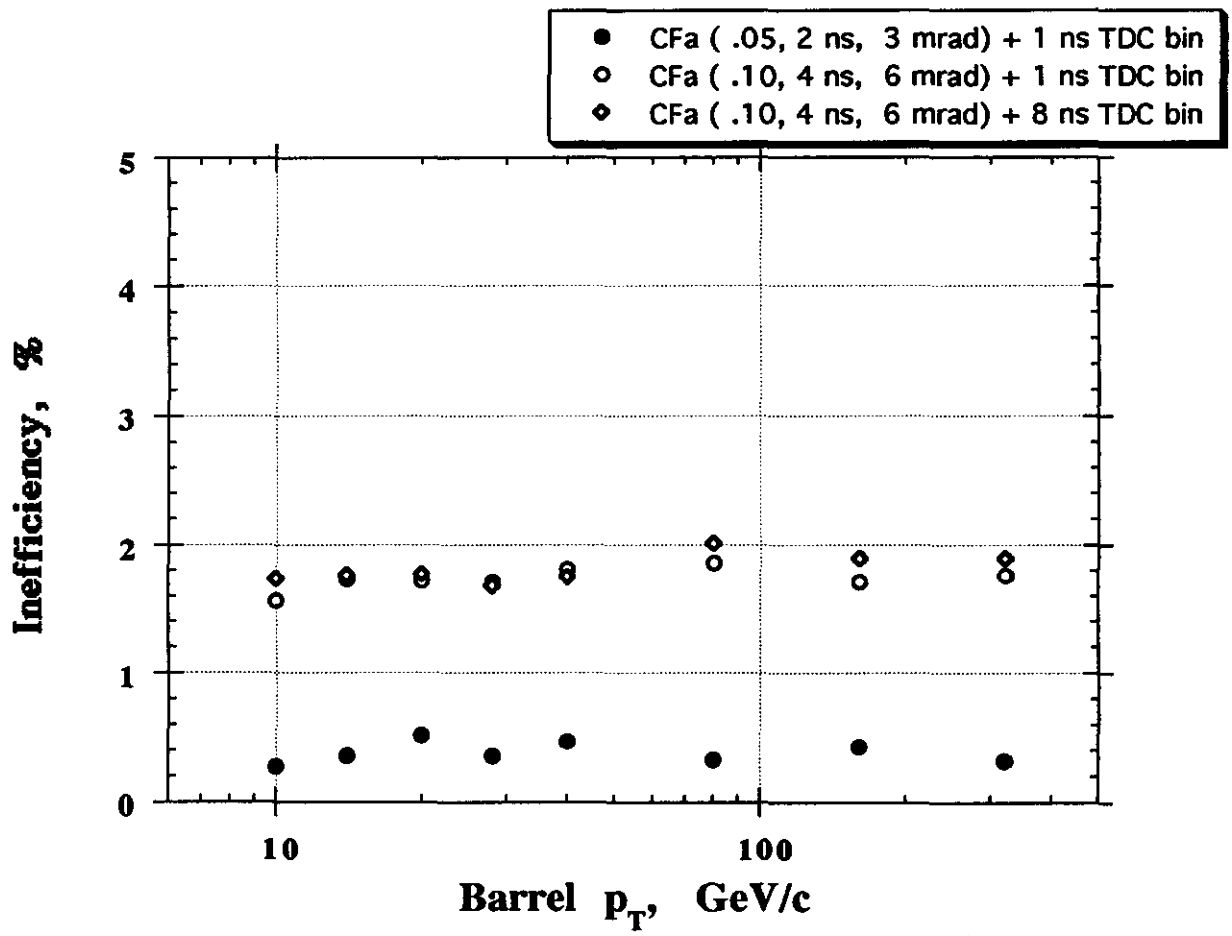

CFa (.05, 2 ns, 3 mrad) + 1 ns TDC bin
CFa (.10, 4 ns, 6 mrad) + 1 ns TDC bin
CFa (.10, 4 ns, 6 mrad) + 8 ns TDC bin
Inefficiency, %
0
1
2
3
4
5
10
100
Barrel p_T, GeV/c

Fig. 9.

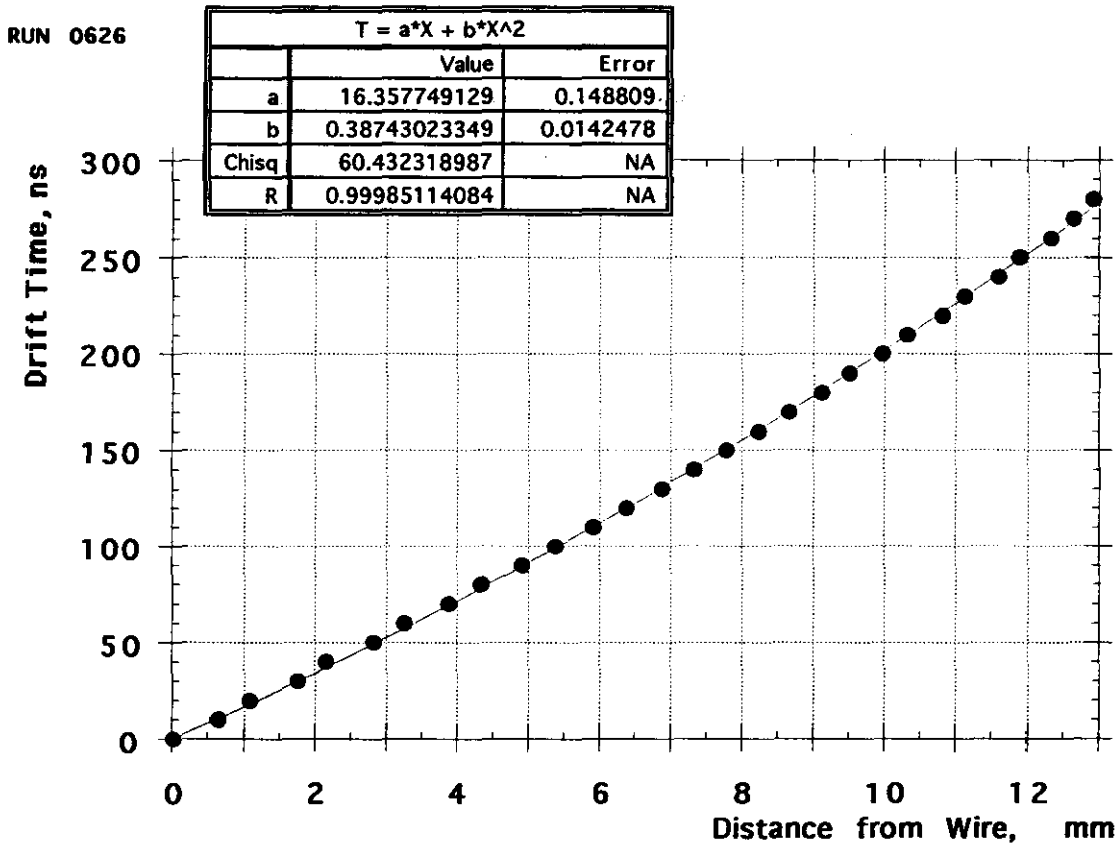

RUN 0626
T = a*X + b*X^2
Value
Error
a
16.357749129
0.148809
b
0.38743023349
0.0142478
Chisq
60.432318987
NA
R
0.99985114084
NA
Drift Time, ns
300
250
200
150
100
50
0
0
2
4
6
8
10
12
Distance from Wire, mm

Fig. 10

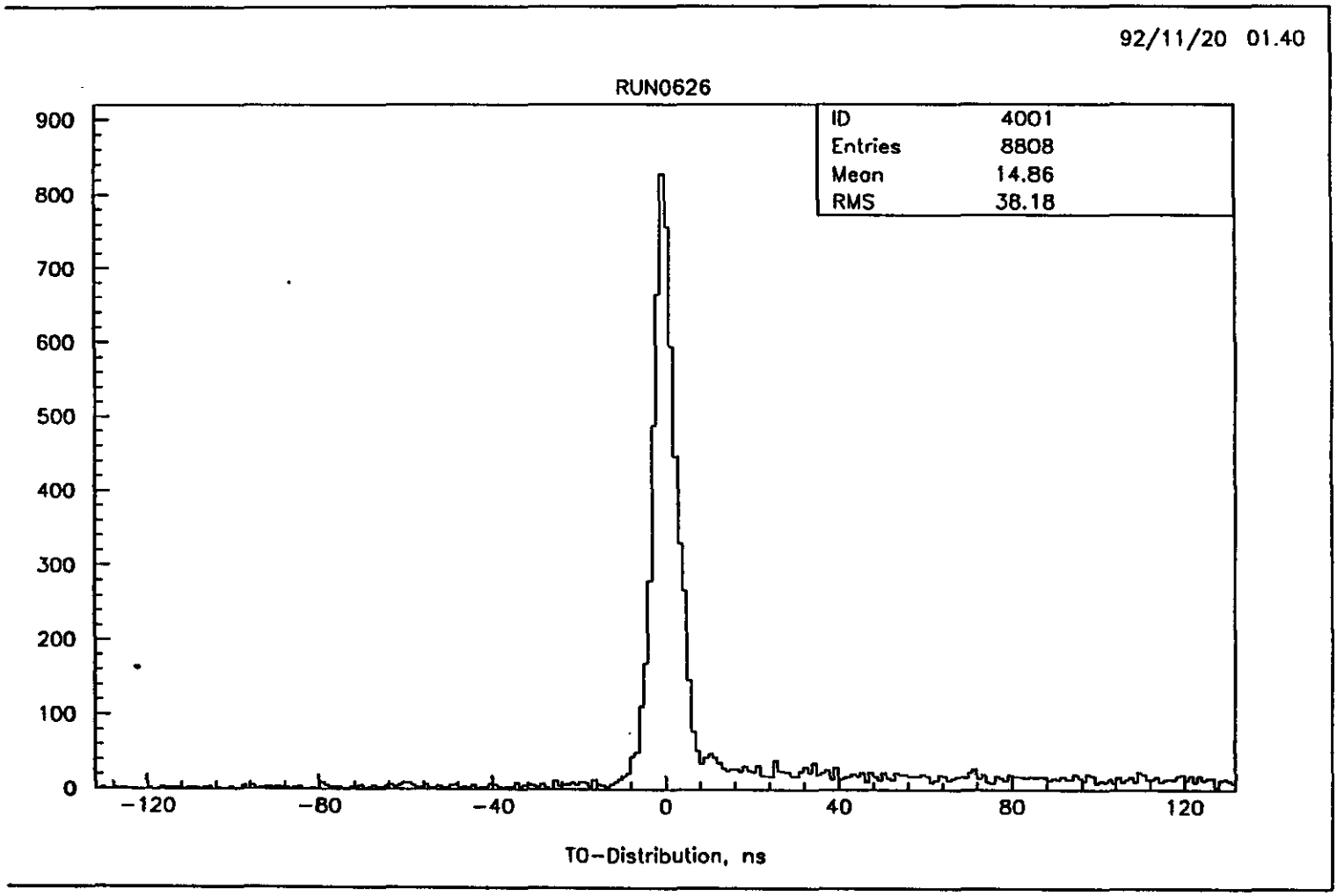

92/11/20 01.40
RUN0626
ID 4001
Entries 8808
Mean 14.86
RMS 38.18
900
800
700
600
500
400
300
200
100
0
−120
−80
−40
0
40
80
120
T0−Distribution, ns

Fig.11(a)

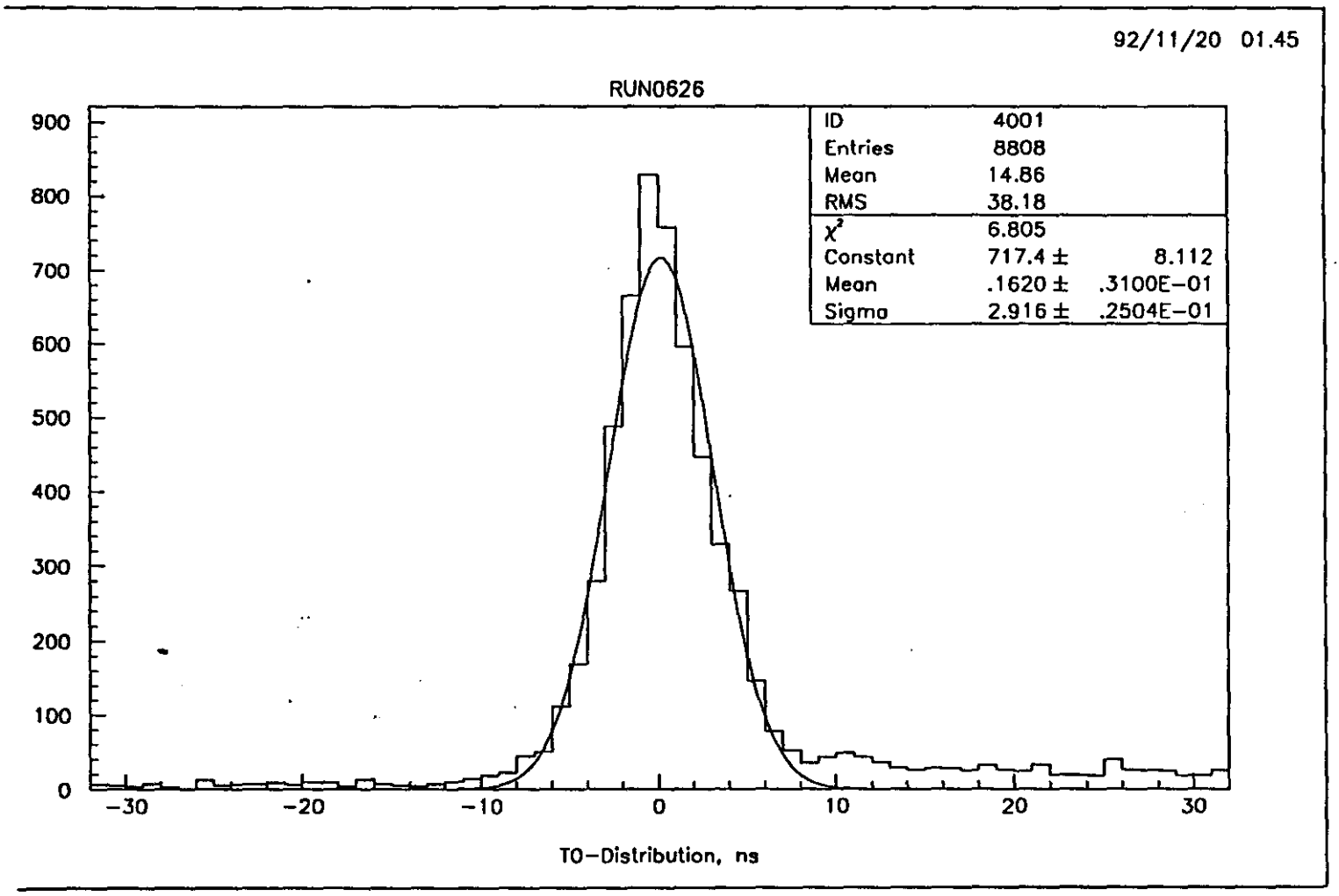

92/11/20 01.45
RUN0626
ID 4001
Entries 8808
Mean 14.86
RMS 38.18
χ² 6.805
Constant 717.4 ± 8.112
Mean .1620 ± .3100E−01
Sigma 2.916 ± .2504E−01
900
800
700
600
500
400
300
200
100
0
−30
−20
−10
0
10
20
30
T0−Distribution, ns

Fig. 11 (b)

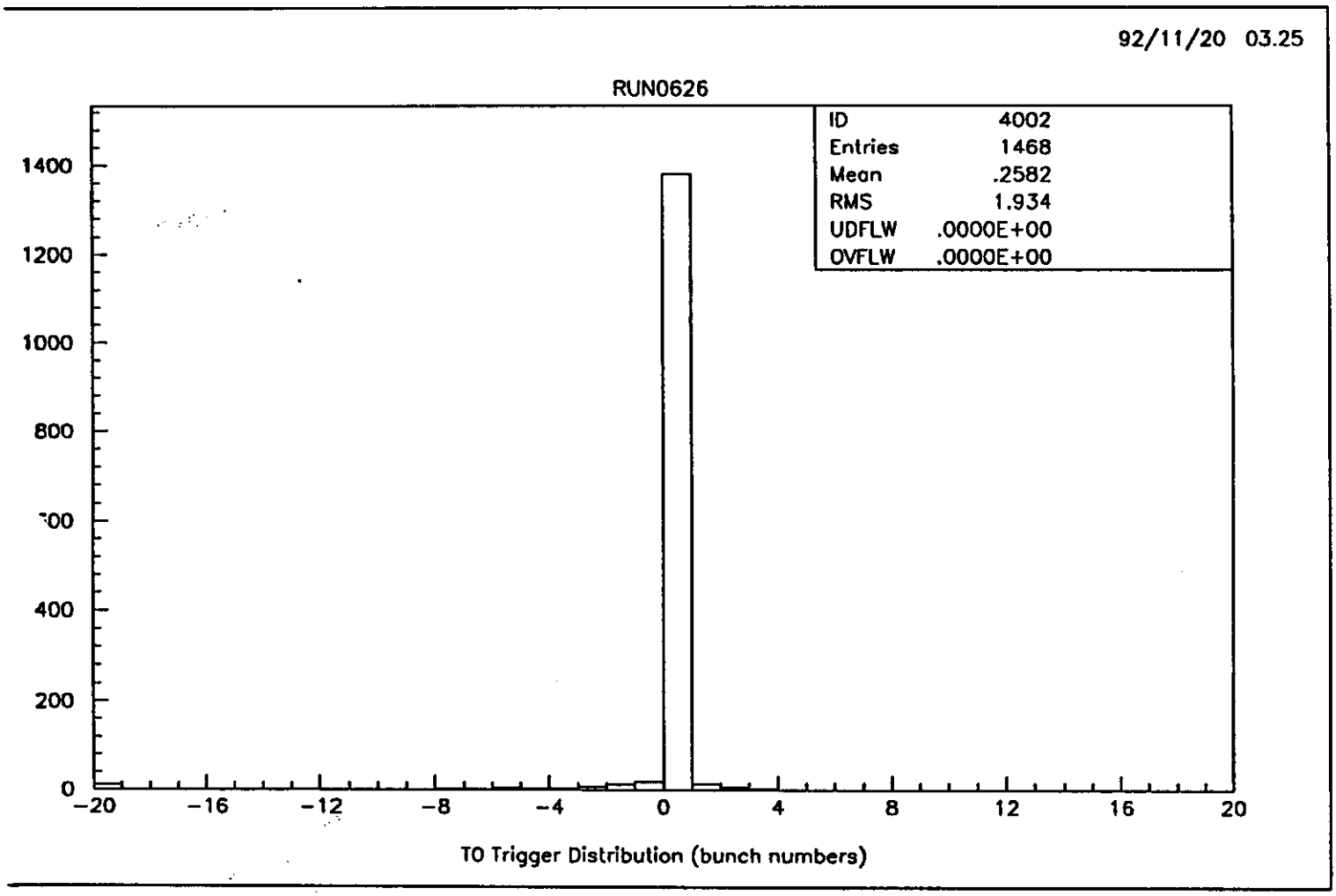
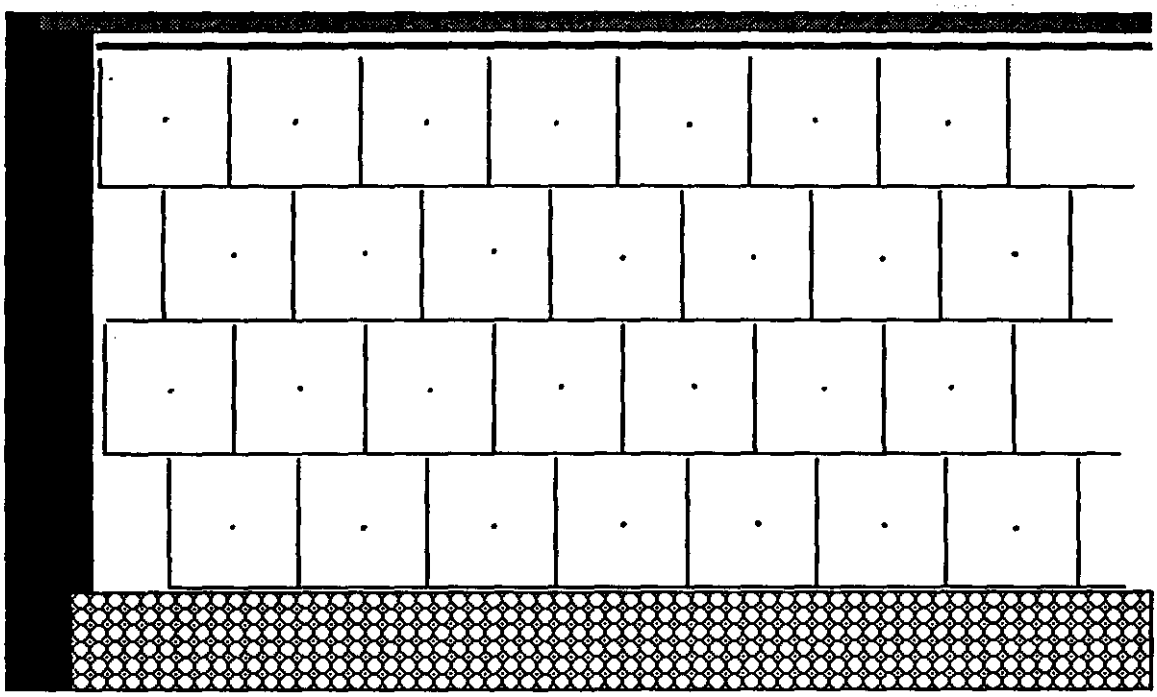

92/11/20 03.25
RUN0626
ID 4002
Entries 1468
Mean .2582
RMS 1.934
UDFLW .0000E+00
OVFLW .0000E+00
1400
1200
1000
800
600
400
200
0
−20
−16
−12
−8
−4
0
4
8
12
16
20
T0 Trigger Distribution (bunch numbers)

Fig. 12



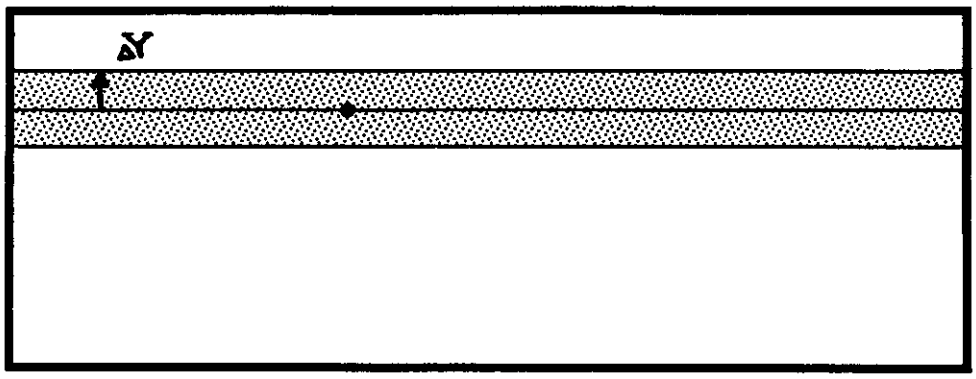
Four plane LSDT chamber

Table 2

	MC	DATA
Right answers	93.6%	94%
Wrong answers	6.1%	5%
No answer	0.3%	1%

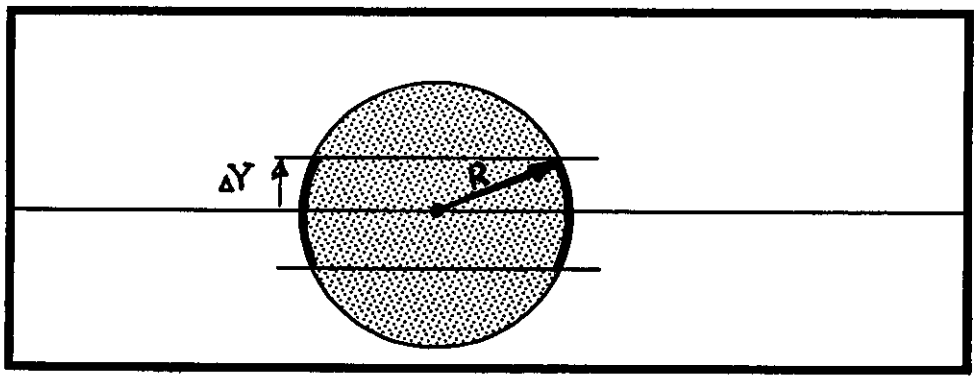
Fig. 13

$$p \sim (2\Delta Y \cdot L) \cdot N \cdot T_{drift}$$



(a)

$$p \sim \left(\frac{2 \cdot 2\Delta Y}{R}\right) / 2\pi$$



(b)

Fig. 14

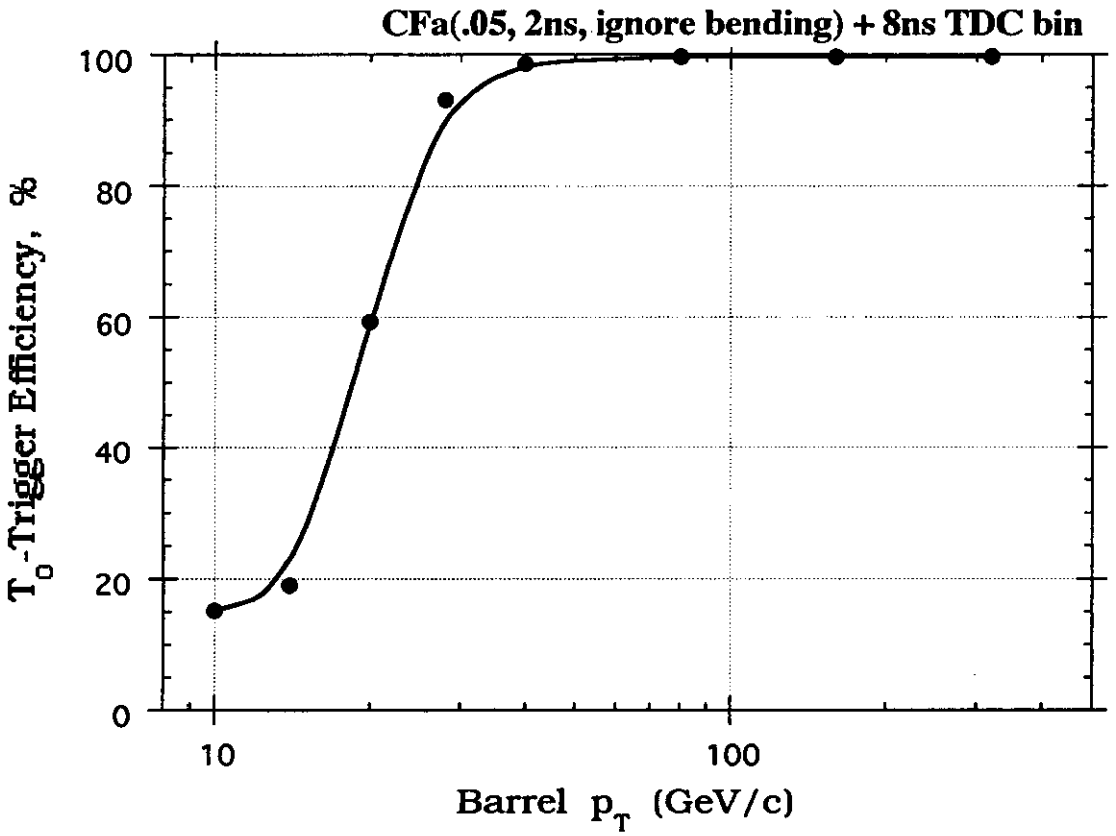
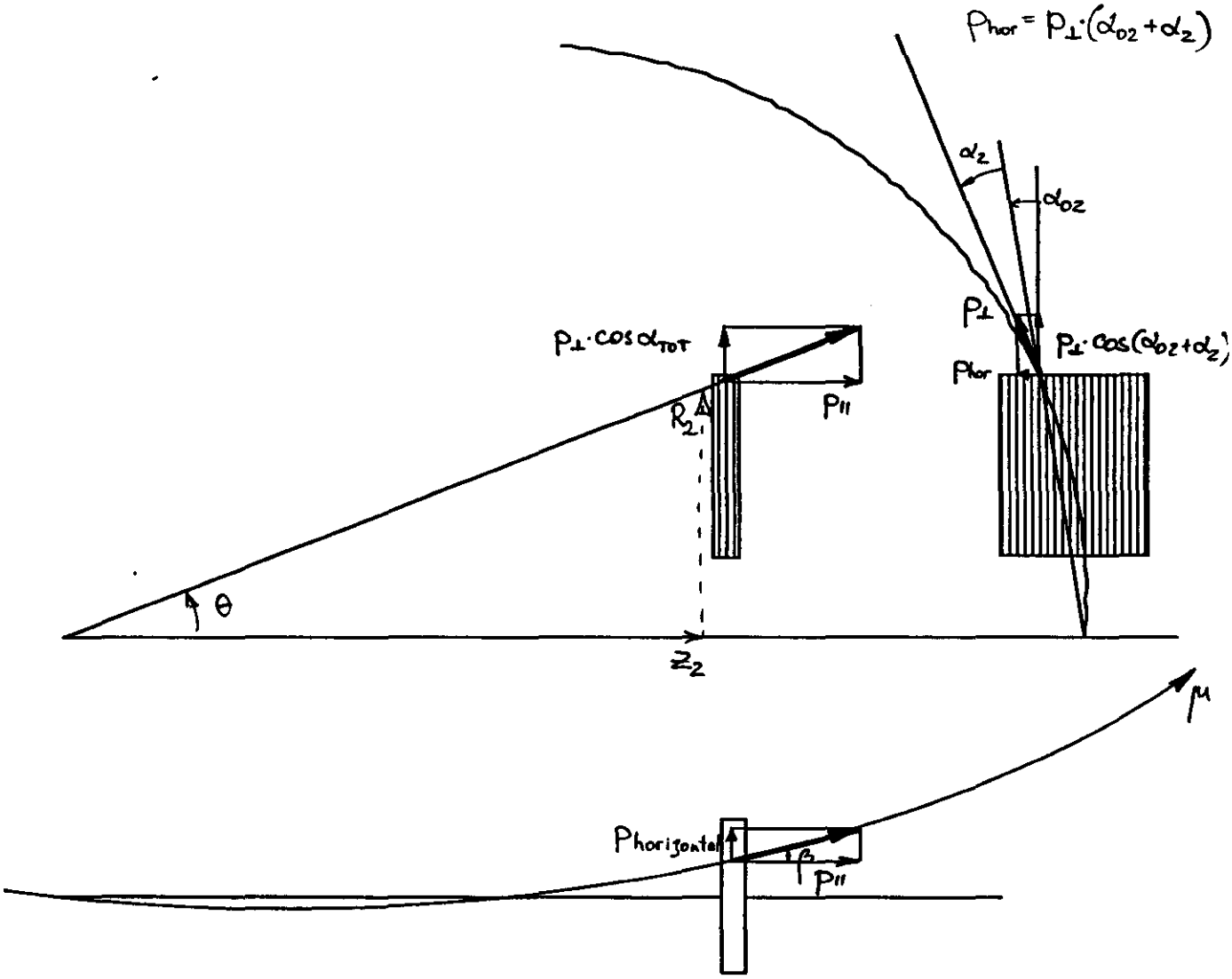

CFa(.05, 2ns, ignore bending) + 8ns TDC bin
100
80
60
40
20
0
10
100
T_0-Trigger Efficiency, %
Barrel p_T (GeV/c)

Fig. 15



$$\beta \sim \frac{p_{hor}}{p_{\parallel}} \sim \frac{p_\perp \cdot (\alpha_{02} + \alpha_2)}{p_{\parallel}} \sim \theta \cdot (\alpha_{02} + \alpha_2) \sim \frac{\theta}{\theta_{max}} \frac{\alpha_{02} + \alpha_2}{2}$$

$$\theta_{max} \lesssim \frac{1}{2}$$

$$\beta_{END\text{-}CUP} \sim \frac{\beta_{BARREL}}{2} \cdot \frac{\theta}{\theta_{max}}$$

Fig. 16

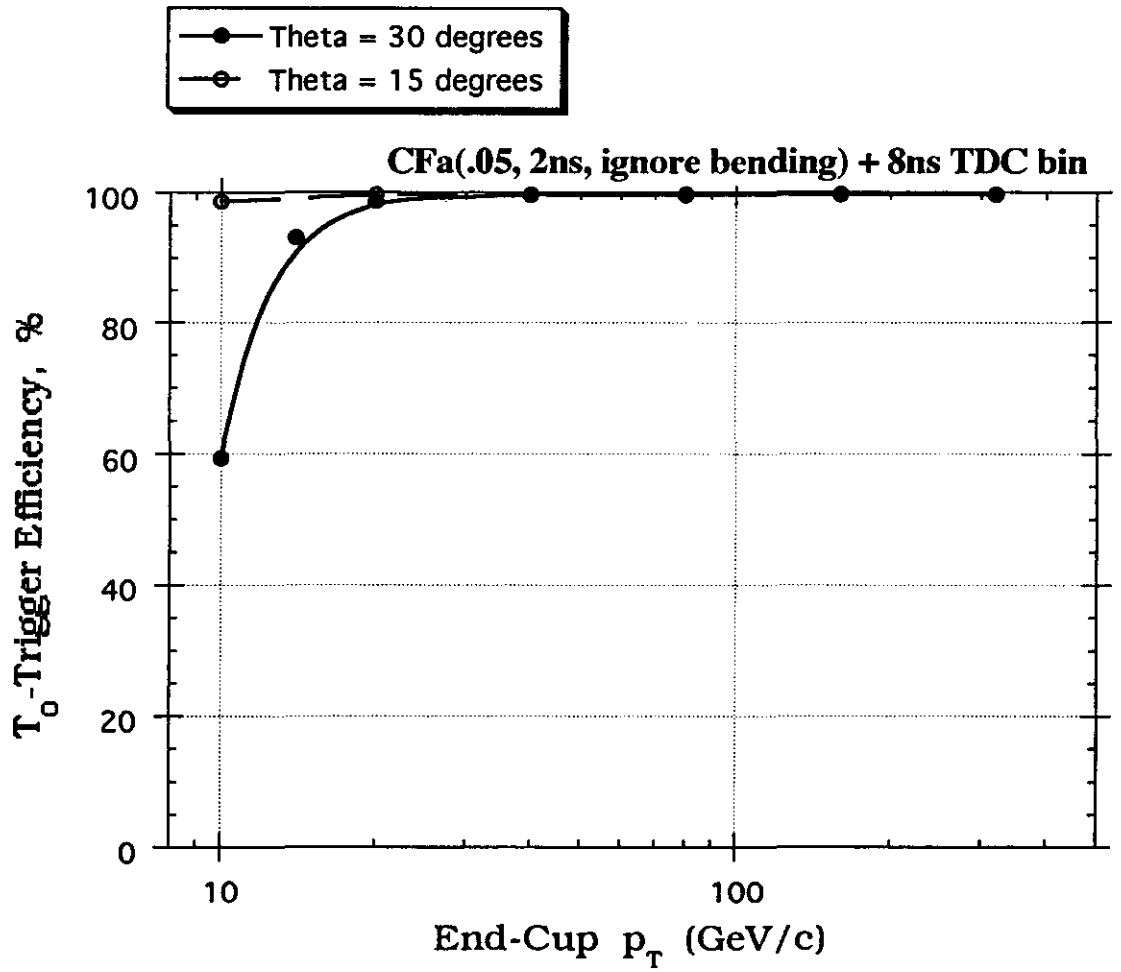

Theta = 30 degrees
Theta = 15 degrees
CFa(.05, 2ns, ignore bending) + 8ns TDC bin
100
80
60
40
20
0
10
100
T_0-Trigger Efficiency, %
End-Cup p_T (GeV/c)

Fig. 17

Appendix 1. Calculations of bending (p_T and/or α_2).

Let horisonatal axis be Y, and vertical - X (fig.1(a)).

An equation for a muon track is

$$Y = \frac{X^2}{2R} + \beta X, \quad \text{where} \quad R = \frac{p_T}{eB} = \frac{X^2}{2R} + \beta X.$$

One can easily calculate Y_3, Y_2, and, then, $\Delta Y=(L_2/L_3)Y_3-Y_2$:

$$\Delta Y = \frac{L_2(L_3 - L_2)}{2R} = \frac{L_2(L_3 - L_2)}{2p_T} eB.$$

One can see that ΔY is indeed a measure of bending:

$$p_T = \frac{L_2(L_3 - L_2)}{2\Delta Y} eB$$

$$\alpha_2 = \frac{\partial Y(L_2)}{\partial X} - \frac{Y_2}{L_2} = \frac{\Delta Y}{L_3 - L_2}$$

Appendix 2. Contribution of Multiple Scattering in the Calorimeter.

1. To calculate T_0, the scheme requires the determination of α_2^T - inclination angle of a track in the SuperLayer#2 (superscript T stands for "Total"). This angle is $\alpha_2^T = \alpha_0 + \alpha_2$, where α_2 is an angle due to track bending in the magnetic field, α_0 is a geometrical angle (angle of a straight line coming out of the vertex). Angle α_2 is momentum dependent and determined as follows (fig.4):

$$\alpha_2 = \frac{d}{\Delta L}, \text{ where } \Delta L = L_3 - L_2 .$$

2. If there is no multiple scattering, the track line is described by the following expression (fig.A2.1):

$$y = \frac{x^2}{2R}, \text{ where } R = p/(eB) \text{ is a radius of cuvature} .$$

A muon coming out of the calorimeter has a y-coordinate y_1 and an inclination angle α_1^T ($\alpha_1^T = \frac{\partial y_1}{\partial x}$). (In the following calculations we will assume that axis X is perpendicular to the chamber. We are looking for the error in determination of angle α_2 and this does not depend on a sector rotation with respect to a muon.)

3. The consequence of multiple scattering is that a muon has some displacement δy_1 and a slight change of an angle $\delta\alpha_1$ in the outcoming point. Let's call for simplicity sake $\delta y_1 = \Delta$ and $\delta\alpha_1 = \theta$. The RMS's and correlation of this parameters depend on the calorimeter thickness and are as follows:

$$\theta_0 = \frac{14.1 MeV}{p}\sqrt{\frac{X_{cal}}{X_0}}; \qquad \Delta_0 = \frac{1}{\sqrt{3}} X_{cal}\theta_0; \qquad \rho_{\theta\Delta} = \frac{\sqrt{3}}{2}$$

4. This results in a change of a trajectory; now it will be:

$$y = \frac{x^2}{2R} + bx + c$$

where $b=\theta$ and $c=\Delta-\theta L_1$ to satisfy new boundary conditions on the calorimeter surface.

5. Actual angle α_2 will be:

$$\alpha_2 = \alpha_1^{\mathrm{T}} - \alpha_0 = \frac{\partial y_2}{\partial x} - \frac{y_2}{L_2} = \frac{L_2}{2R} - \frac{c}{L_2} .$$

(Notice that this does not depend on the sector rotation).

6. Angle α_2 as measured ($\alpha_2 = \frac{d}{\Delta L}$):

$$\alpha_2^{meas} = \frac{\frac{L_2}{L_3} y_3 - y_2}{\Delta L} = \frac{1}{\Delta L}\left(\frac{L_2}{L_3}\left(\frac{L_3^2}{2R} + bL_3 + c\right) - \left(\frac{L_2^2}{2R} + bL_2 + c\right)\right) = \frac{L_2}{2R} - \frac{c}{L_3}$$

7. Error in Angle Measurement:

$$\delta\alpha_2 = \alpha_2^{meas} - \alpha_2 = \frac{c}{L_2} - \frac{c}{L_3} = (\Delta - \theta L_1)\frac{\Delta L}{L_3 L_2}$$

Taking into account RMS's and correlation function one gets:

$$\overline{\delta\alpha_2^2} = \theta_0^2 (L_1^2 - L_1 X_{cal} + \frac{1}{3} X_{cal}^2)\frac{\Delta L^2}{L_3{}^2 L_2{}^2} .$$

Using the LOI numbers (L_1=3.9m, L_2=6.3m, L_3=8.7m, X=2.5m, Cu calorimeter of effective 12λ thickness) for p=10 GeV/c one get **the angle error of about δα~.002, what is smaller than the assumed measurement error (and, of course, it is far away from the biggest tolerable error)**.

8. Momentum Error Due to Multiple Scattering.

The angle α_2 gives a measure of p_T.

Without multiple scattering:

$$\alpha_2(no\ \mathrm{m.s.}) = \frac{L_2}{2R} = \frac{eBL_2}{2p} .$$

Due to multiple scattering, the measured angle will have an error:

$$\delta\alpha_2 = \alpha_2^{meas} - \alpha_2(no\ \mathrm{m.s.}) = -\frac{c}{L_3},$$

what corresponds to momentum error of **δp/p~.066**.

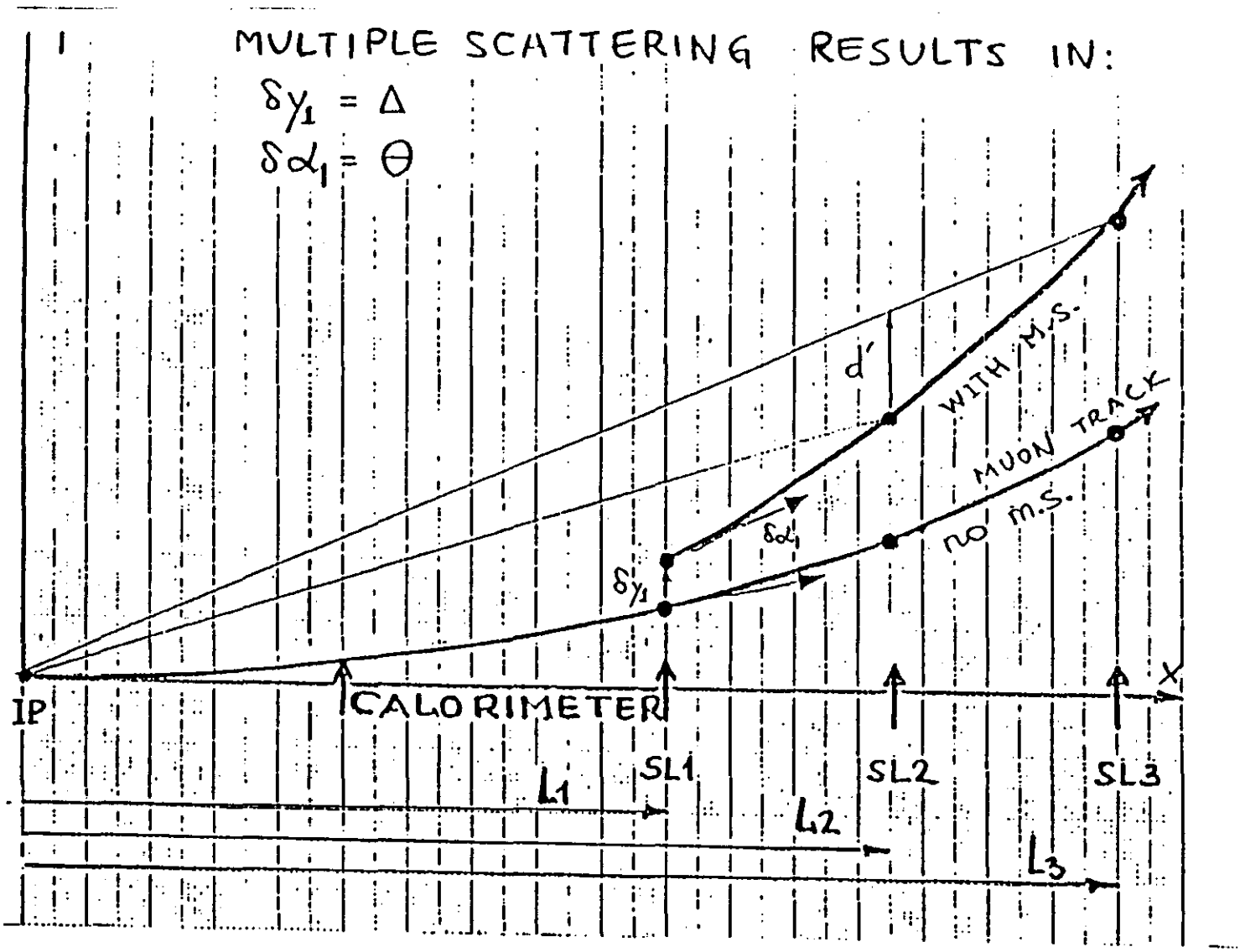

MULTIPLE SCATTERING RESULTS IN:
$\delta y_1 = \Delta$
$\delta \alpha_1 = \Theta$
d'
WITH M.S.
MUON TRACK
NO M.S.
$\delta \alpha_1$
δy_1
IP
CALORIMETER
SL1
SL2
SL3
X
L_1
L_2
L_3

Fig. A2.1

R. Sumner, October 1992

Appendix 3 : Hardware Implementation of the Level 1 Trigger

The basic muon trigger is a local 4 layer coincidence of the 4 layers in a superlayer. When this occurs a small amount of dead time is incurred in that muon chamber only. The local coincidence is formed in hardware which is attached to each wire. The remainder of the trigger uses hardware which is shared among all wires in a muon chamber. For a valid track, the trigger output consists of the corrected beam crossing time, the bend angle of the track, and the Phi and Z coordinates of the local track segment. The global portion of the muon trigger must correlate the information from all muon chambers.

The basic trigger group is 16 drift cells, 4 in each of the 4 layers. The maximum drift time is 300 ns. The maximum signal transit time is 50 ns (for a 6 M long wire).

The output of each cell (drift wire) is input to a pipelined TDC similar to the precision TDC but with less resolution. This must be logically independent from the precision TDC. The resolution is 4 ns, so it divides the beam crossing interval into 4 parts. The pipeline is as long as the drift time in the drift cells plus the transit time. There is an OR output which is the OR of all of the pipeline stages, and indicates that there is a hit somewhere in the pipeline. Note that there is one pipeline for each wire in the chamber.

These pipeline ORs are then ORed with adjacent cells (in the same layer and same basic group) to form a layer OR. This is ANDed with the 3 other layers to form the local 4 fold coincidence. To avoid the problem of track sharing between 2 adjacent trigger groups, the adjacent groups are paired to form overlapping coincidence trigger groups of 32 cells, 8 in each of the 4 layers. The corresponding layer ORs are ORed together before the 4 fold AND.

When the 4 fold coincidence is detected the trigger system enters the second phase, and deadtime begins. The processing hardware cannot accept another 4 fold coincidence until this trigger is completed. The TDC data leaving the pipeline is extended (by adding a step count since the coincidence detection) and stored in a register at the end of the pipeline. After waiting the drift time (plus the wire transit time), the entire pipeline has been searched for data. All detected hits are now converted to time and are stored in local registers. The pairs of wires which are linked at the far end are examined to produce the cell struck and the Z position (1 M resolution). This logic is most naturally part of the TDC IC, and is not shared, but is replicated for each wire pair.

The 4 fold coincidence also triggers the rest of the trigger logic, which is shared by all wires in the chamber.

This hit cell pattern is now examined. Of the 4096 possible patterns of 1 hit per layer, only about 200 correspond to straight tracks within +- 17 degrees from the normal (10 Gev muon cutoff). The 12 bit pattern (3 bits per layer) is used as the input to a lookup table. If the pattern does not match, the trigger is aborted, and the dead time (less than 450 ns) is over. The 4 Z coordinates are simultaneously checked for consistency. The outputs of this stage are the Phi and Z coordinates of the track candidate.

If the pattern is valid, the time is examined, and a new pattern is formed using the time data to reduce the cell size. This new pattern (11 bits, a relative pattern, independent of Phi) is also used to enter a lookup table. There are only about 300 valid patterns out of the

2048 available. The presence of a delta ray will typically transform a valid pattern into an invalid one. There are three outputs, the track angle (with respect to the chamber), instructions for calculating the beam crossing time (which time pairs to use, and their polarity), and the beam crossing time correction (due to the angle).

The next step is to subtract the selected pairs of time measurements, and add the correction. This results in up 6 beam crossing times. Using either combinatorial logic, or a sequence of lookup tables, the times are compared, and a majority logic decision made. The Z correction (flight time from interaction point) is included in this step, as is the non linear drift characteristics of the chamber gas.

Simultaneously with the beam crossing calculation the Phi coordinate is used to extract the bend angle from the observed chamber angle (again, lookup tables). This bend angle will be known to 1 degree rms or better.

The final result from this trigger system is the beam crossing time, the bend angle, and the Phi and Z coordinates of the track.

A preliminary estimate of the trigger processing time. The drift and transit times cannot be reduced. The processing time estimates are an upper limit.

drift time + transit time	350 ns
cell pattern table lookup	100 ns
time pattern table lookup	100 ns
beam crossing calculation	100 ns
beam crossing selection	100 ns
total time	750 ns

This simple trigger scheme is not very robust. It does have some inherent rejection of delta rays, during the table lookup of the time pattern, but not enough redundancy to do much more than reject a trigger accompanied by a delat ray. The trigger can be made more robust by adding another layer to the superlayer (for a total of 5 layers). If the trigger uses the middle superlayer (which consists of 2 4 layer chambers), 8 layers would be available for the beam crossing calculation.

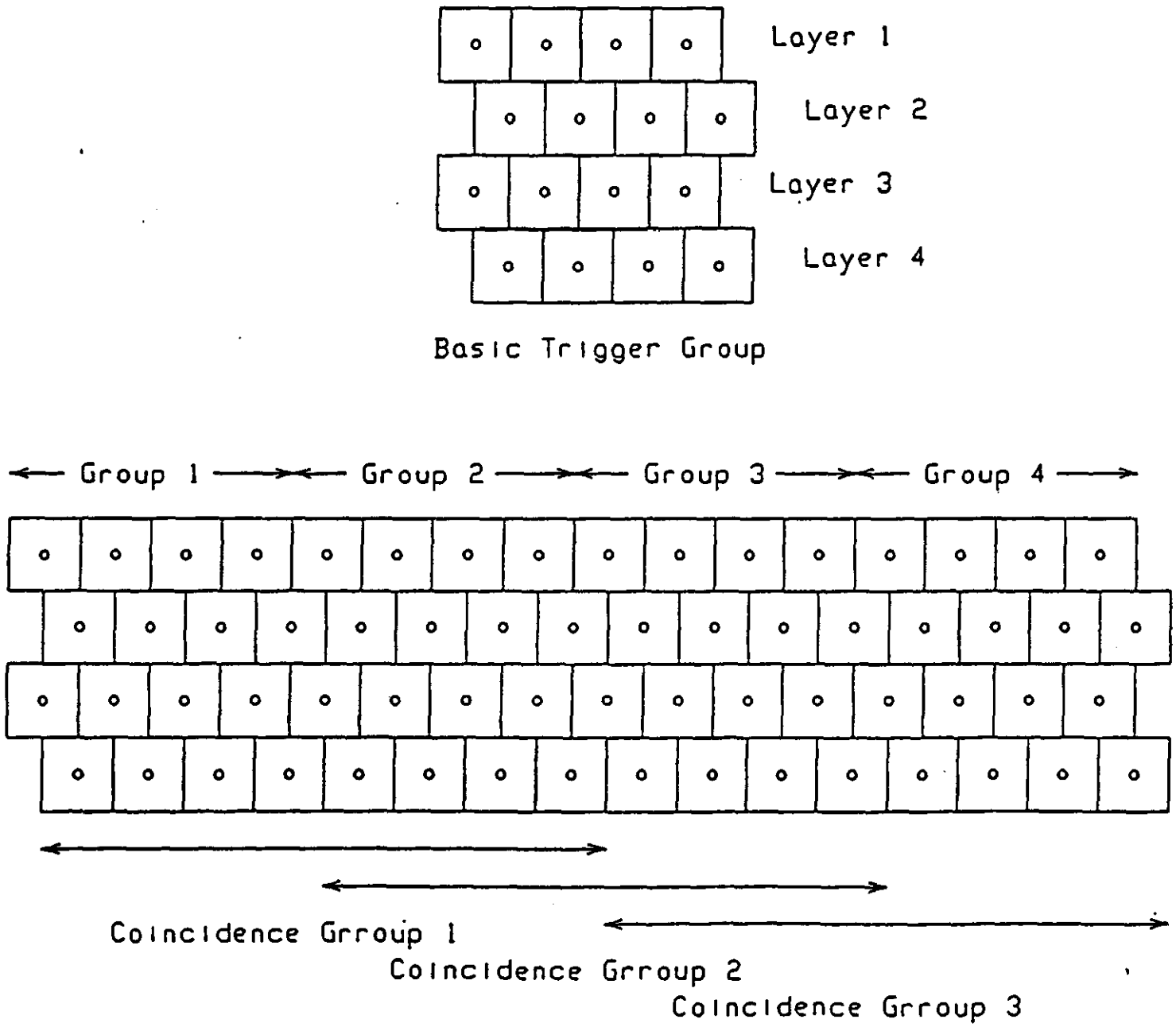

Layer 1
Layer 2
Layer 3
Layer 4
Basic Trigger Group
Group 1
Group 2
Group 3
Group 4
Coincidence Grroup 1
Coincidence Grroup 2
Coincidence Grroup 3

Fig.A3.1.

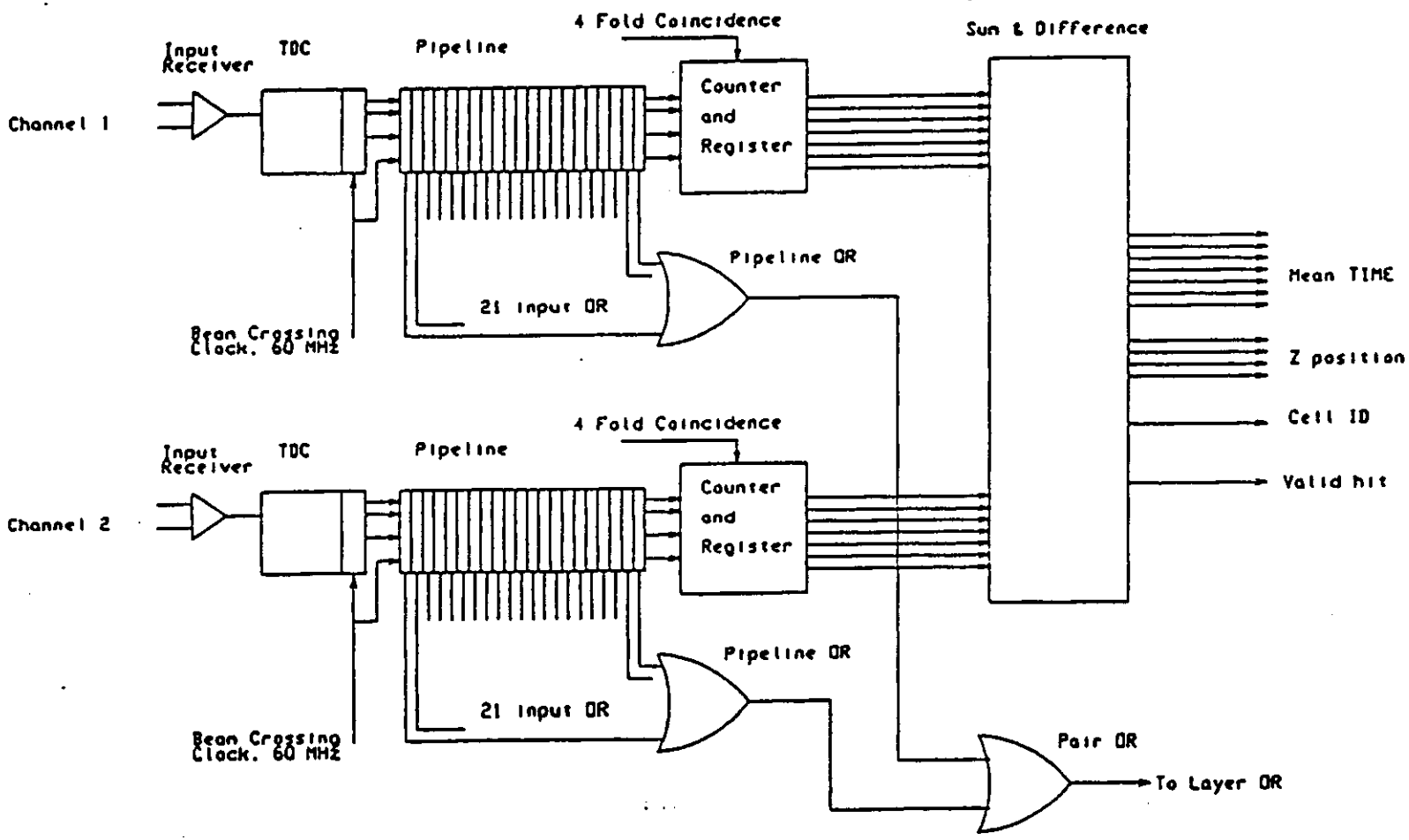


Fig.A3.2 Muon Trigger TDC

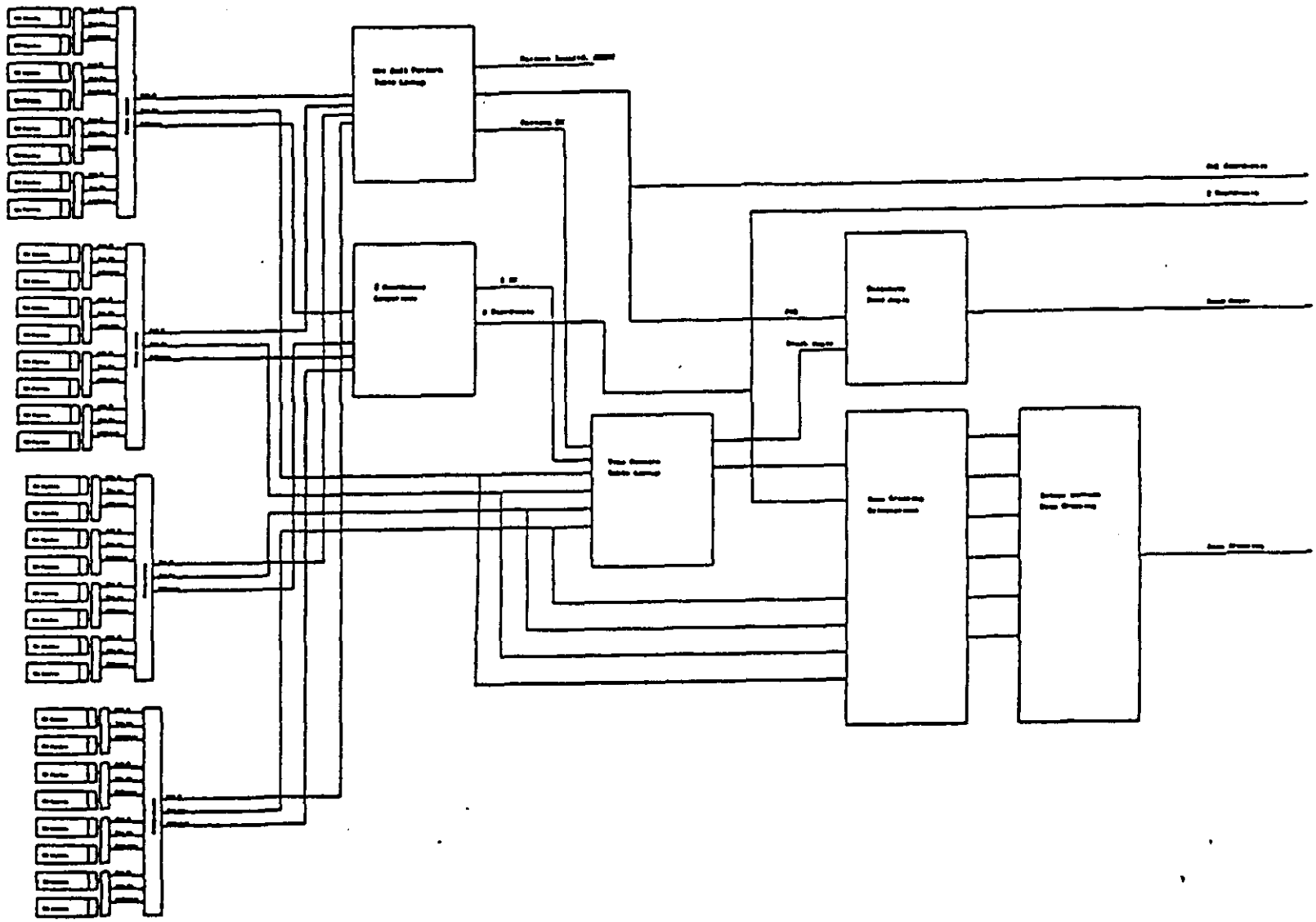


Fig.A3.3

Appendix 4.

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September 23, 1992

A Short-Delay-Time Implementation of the LSDT Trigger

Recently, Korytov proposed a trigger scheme for the GEM LSDT's suitable for determining the bunch crossing for the Level 1 trigger. Korytov's analysis shows that for staggered square tubes of transverse dimension D (see figure 1) having a time-distance relationship of the form

$$t_i = ad_i + bd_i^2$$

where t_i is the drift time of charge originating a distance d_i away from the wire, T_0, the absolute time of the particle's incidence, is given by

$$T_0 = \frac{(t_1 + t_2)}{2} - \frac{aC_0}{2} - \frac{b}{4}\left[C_0^2 + \frac{\Delta T^2}{(a + bC_0)^2}\right]$$

where $\Delta T = t_1 - t_2$ and

$$C_0 = \frac{D}{2} + \alpha D \qquad \text{and} \qquad \alpha = \tan\theta$$

where θ is the angle of incidence (zero for normal incidence).

The first term in the expression for T_0 is just $\bar{t} = (t_1 + t_2)/2$, the mean time of arrival of the two pulses. Note that for a linear gas ($b = 0$) and normal incidence ($\alpha = 0$) the second and third terms vanish, apart from a fixed constant. In practice these terms are not zero, but they can be viewed as corrections to the mean time, i.e.

$$T_0 \equiv \bar{t} + \Gamma(\alpha, \Delta T) + t_0$$

where t_0 is a constant offset. Figures 2a shows the additive time correction as a function of momentum, which is closely related to α; and figure 2b shows the corrections as a function of ΔT for various choices of α.

Circuits capable of performing the meantiming function in realtime can be implemented in a number of ways. A popular approach is shown in figure 3. As the figure suggests, the same circuit has been used in past high-energy physics experiments to correct for position dependence in long scintillators. In practice the delays can be implemented using logic gates, permitting very fine granularity. Although the *time* at which the first AND-gate coincidence is satisfied depends only on $\bar{t}$, the *position* of the first AND gate to fire depends on ΔT. Thus by adding small amounts of extra circuitry (a priority encoder) one can devise a circuit that simultaneously meantimes its inputs and produces a binary word proportional to ΔT.

This block can in turn be incorporated into the system shown in figure 3. The pulse emerging from the meantimer is delayed (slightly) allowing enough time for the ΔT information to be combined with a binary representation of α to form an address for the

memory lookup unit (MLU). The contents of the MLU are loaded with the required correction time—i.e. they contain the function $\Gamma(\alpha, \Delta T)$. The value of Γ is then used to dynamically adjust the delay time such that a pulse emerges at time T_0 (plus a constant). One simple implementation of the adjustable delay is a presettable down-counter, although it may prove desirable to seek designs based solely on asynchronous logic, as discussed below.

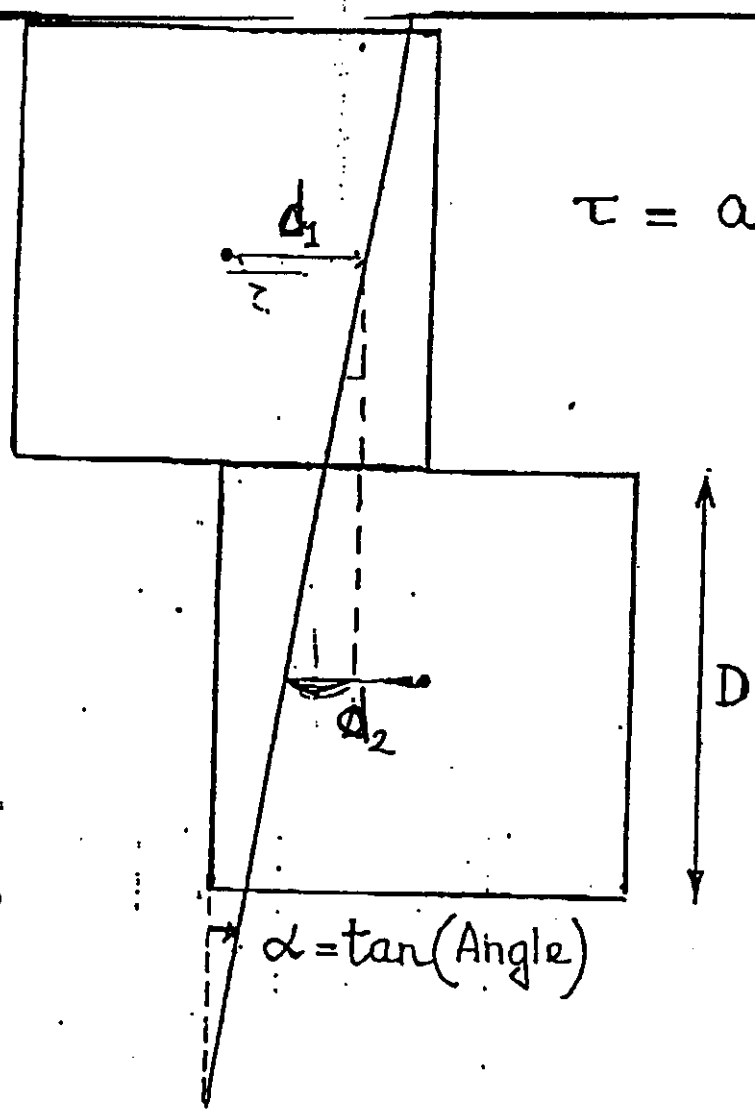
For values of α and ΔT of practical interest, Γ is always less than $\sim$ 100 ns or so. Requiring $\leq$ 4 ns of "quantization error" in Γ leads to the need for only five or six bits of accuracy. Assuming comparable accuracies for α and ΔT are required, the number of address lines to the MLU is in the range of 10 to 12 bits, a modest size by today's standards.

The outputs of the corresponding circuits from other left right wire pairs can be combined using a standard majority logic circuit that requires a specified multiplicity. This will provide immunity to noise and to the (presumably) small number of cases where the T_0 signal from a given pair comes out of time.

For normal incidence the latency time of this scheme is the drift time plus the fixed delay of the meantimer. In the implementation shown this is one half of the maximum drift time, yielding a total latency of 1.5 times the total drift time. The MLU also adds some delay, but this can be kept to a few tens of ns. Finally, some allowance must be made for non-normal incidence, which will also add to the latency, but this is probably less than 100 ns. We note that there is some room left between the latency of this circuit and the irreducible limit imposed by causality, suggesting that further improvements are possible. This would require a meantimer design with no fixed propagation delay.

Another such concern in any such scheme is the deadtime. For schemes employing sequential logic, this will likely be of the same order as the latency. If, however, a pipelined version of the adjustable delay can devised—this should be possible—the entire circuit can be fully pipelined. In this case, the effective deadtime can be reduced to the few $\times$10 ns level. An added benefit would be the elimination of the need for a high-speed clock.

One loose end in this design is the determination of α, which will require additional circuitry. This could entail some additional latency due to propagation delays since α is an inherently non-local quantity.



$$\tau = a \cdot \Delta + b \cdot \Delta^2$$

$$T_0 = \frac{t_1 + t_2}{2} - \frac{a \cdot C_0}{2} - \frac{b}{4}\left(C_0^2 + \frac{(\Delta T)^2}{(a + bC_0)^2}\right)$$

$$C_0 = \frac{D}{2} + \alpha \cdot D$$

Figure 1 (App.4)

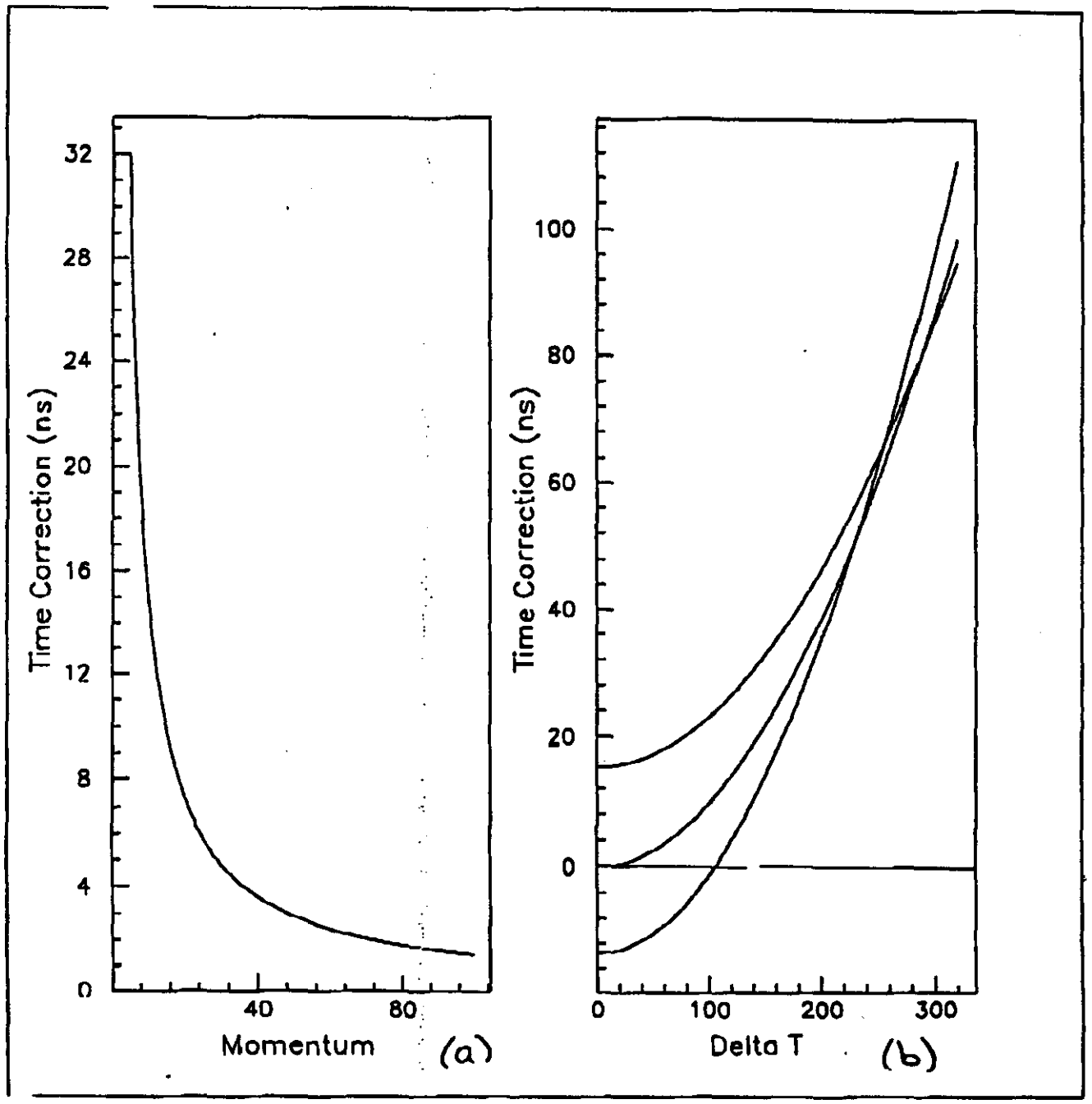


Figure 2 (App. 4)

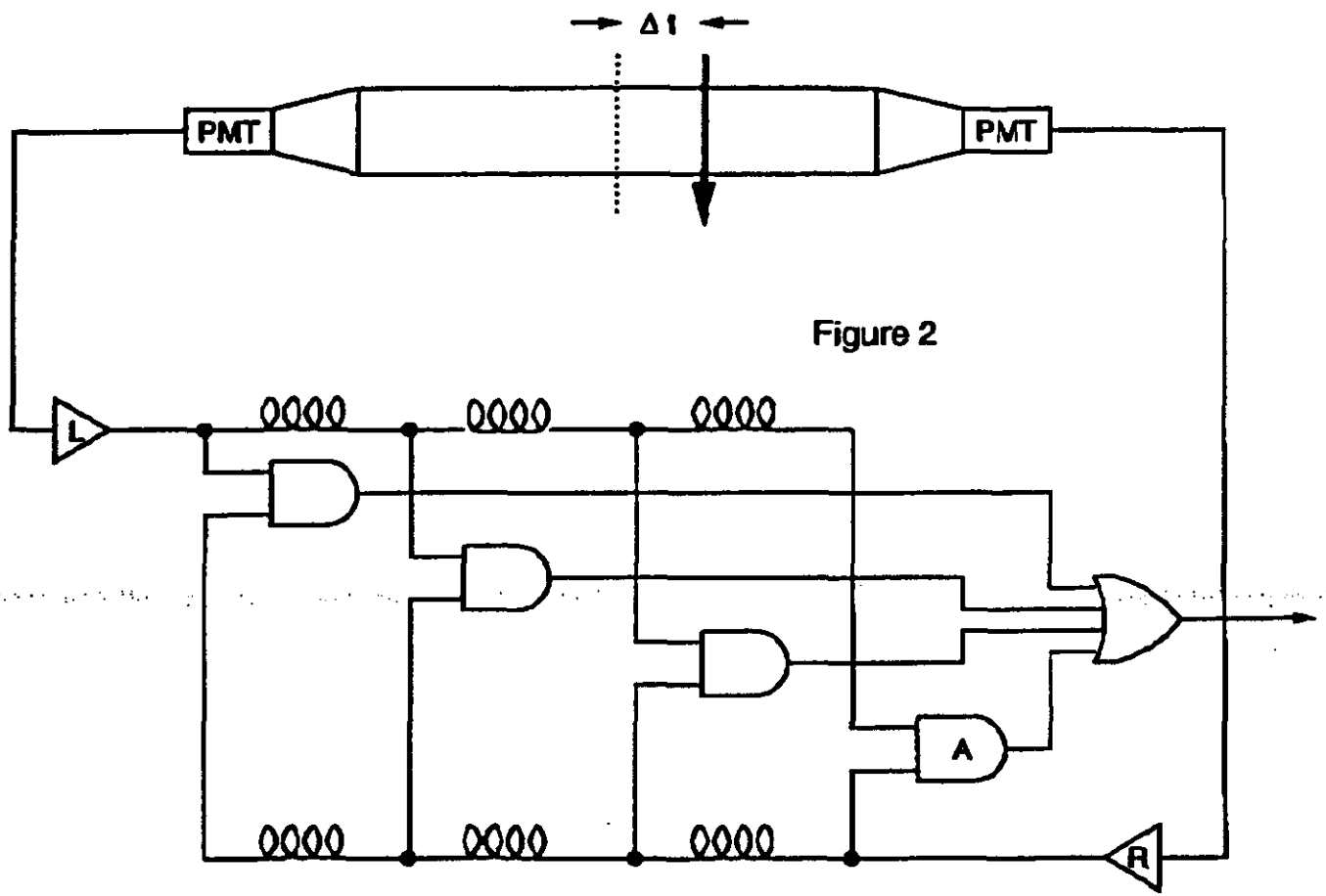


Figure 2

Figure 3 (App. 4)

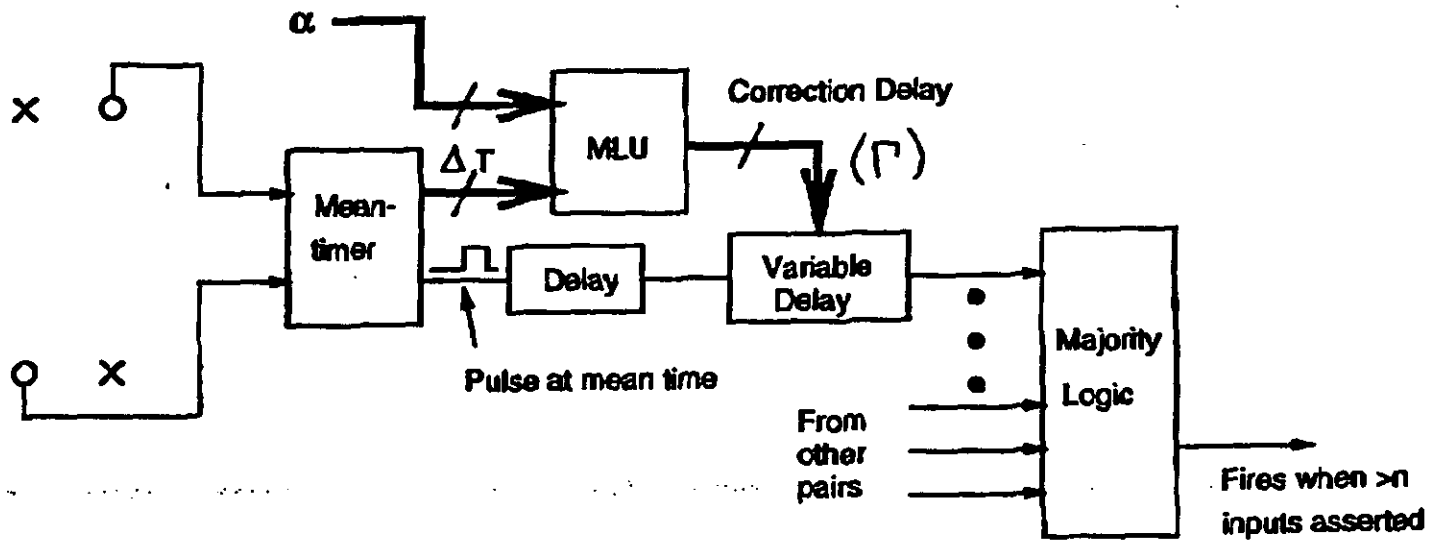


Figure 4 (App. 4)