

CLAS-NOTE-91-027

Further Studies of Light Guides for CLAS-TOF Scintillators*

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Introduction

The design of the CEBAF Large Angle Spectrometer (CLAS) places constraints on the size and shape of light guides used with scintillators and photomultiplier tubes (PMTs) in the time-of-flight (TOF) system [1]. To cover large angles and enhance timing characteristics, both ends of each scintillator will be connected to a light guide, which will then be coupled to a PMT. The type of light guide used will be determined by physical constraints within the CLAS, timing characteristics and relative cost.

In an extension of work previously done here [2], we have tested seven different types of light guides compatible with the TOF scintillators planned for the CLAS. Three types are straight triangular lucite light guides 5 cm thick by 20 cm wide that fit to the scintillator at the base of the triangle and are coupled to the PMT at the apex (See Figure 6). Three other guides are triangular but are bent out of the plane of the scintillator (See Figure 7). These were made out of one (2.5 cm), two (each 1.25 cm) and four (each 0.63 cm) pieces of lucite, respectively. In general, a larger number of thinner pieces in a bent light guide results in better light collection, and hence better timing, but more difficult construction. We also tested an air light guide made of reflective metal (Everbrite, Alcoa Aluminum) in the shape of the solid light guides. The goal of this experiment has been to achieve timing resolution of 120 to 200 psec for the equivalent of minimum ionizing particles passing through a 5 cm plastic scintillator (10 MeV) and to compare the timing resolution of the different light guides at this level.

Experimental Design

Figure 1 shows the setup used in the laboratory. An 80 cm x 20 cm x 5 cm NE110 scintillator had a light guide connected to each end. On the end of each light guide was a Philips XP2020 photomultiplier tube. The PMTs were run at -2000 V with Products For Research Inc., PR1406RF tube bases. A UV light pulser [3] was used as the source of light transmitted through the scintillator and to the PMT. The pulser, a quartz tube containing H₂ gas at about 130 Torr, was run at 4000 V, at a pulse rate of 263 Hz. The amount of light passed into the scintillator could be controlled by an aperture wheel with nine different apertures. From the aperture wheel, the light passed through a 4 mm diameter plastic fiber to a rectangular piece of lucite at the top-center of the scintillator. The rectangular piece of lucite had a 4 mm dia. hole drilled into it to accept the fiber.

Each of the PMT outputs was sent to a Phillips Scientific Model 715 Constant Fraction Discriminator, as was the negative pulse generated by a photodiode coupled to the pulser. The three discriminator outputs were used

Experimental Design

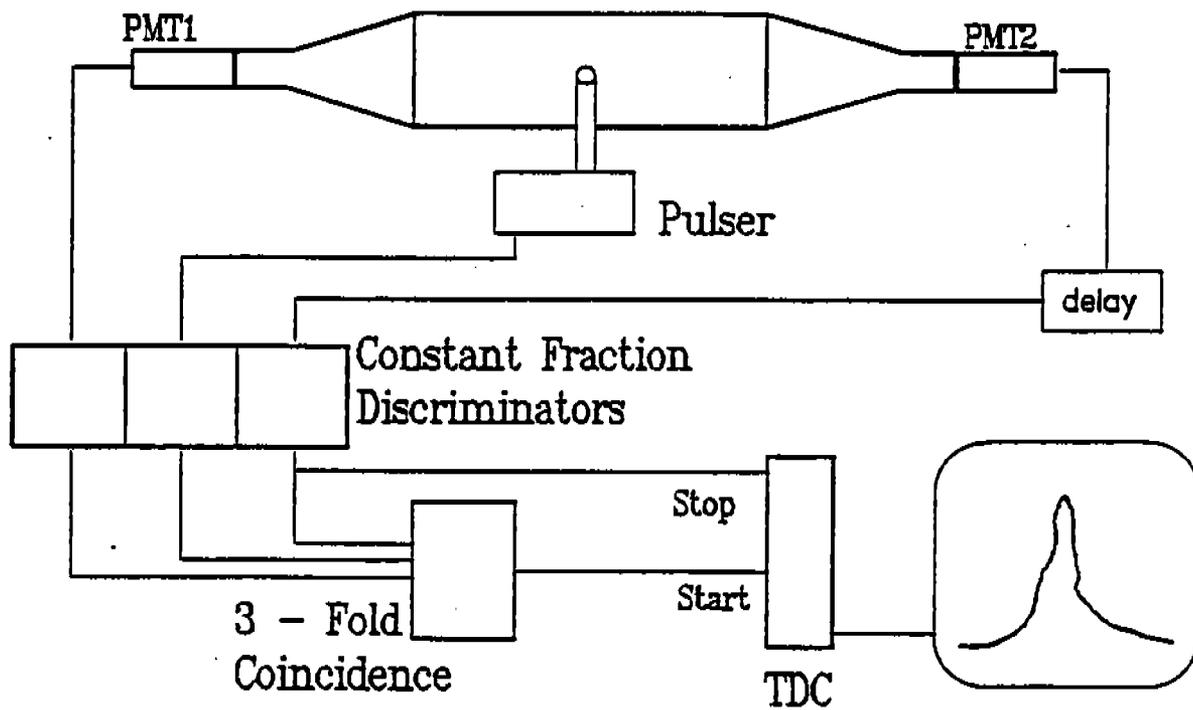


Figure 1. Schematic diagram of the experimental equipment.

in coincidence to start the TDC. Discriminator 1 had a very narrow output and Discriminator 2 and 3 had wide outputs. A delayed output from Discriminator 2 served to stop the TDC. Thus, the start of the TDC was essentially by PMT1 but it occurred only when there was a stop from PMT2 and both signals originated from the pulser.

Experimental Procedures

Before testing the light guides, experimental parameters were sought that achieve the best possible timing with two straight light guides. These parameters include a) the high voltage setting of the PMTs; b) the discriminator levels; c) and the discriminator delays. The goal for the CLAS TOF scintillators is a time resolution, $\sigma_c = 120$ psec when 10 MeV is deposited in the scintillator.

The choice of parameters concerned practicality as well as timing. As stated earlier, the PMTs were operated at -2000 V to the photocathode. When 10 MeV was deposited in the scintillator, the PMTs gave out signals of the order of -80 mV in pulse height. Thus, the discriminator levels were set as low as possible, -25 mV. Though the XP2020 output signals had very short rise time (2-3 nsec) in most situations, a few tests were made with additional capacitance added to the light pulser resulting in a light pulse of intrinsic rise time of 5-6 nsec. The adjustable cable delays on both CF discriminators were chosen at 6 nsec.

The optical connections -- between scintillator, LGs and PMTs -- were

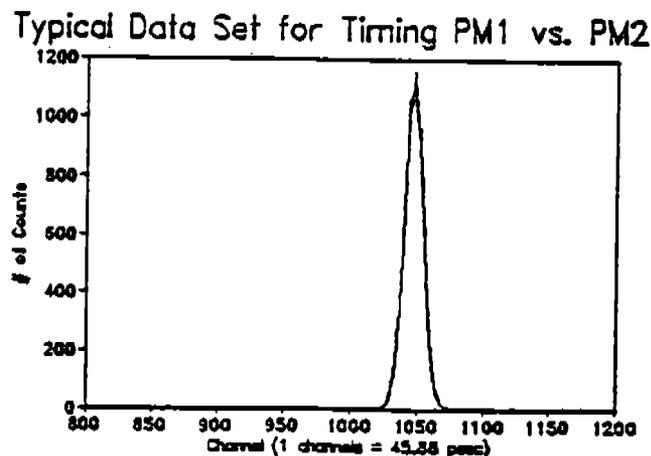


Figure 2. A typical set of data timing PMT 1 and SS LG vs. PMT2 and 1S LG. Here $\sigma_{diff} = 7.29$ chn.

all made with optical grease. The lucite light guides were wrapped with aluminum foil to enhance reflection. These and the air light guide were wrapped with layers of black plastic to make the assembly light-tight. Once the light guides were coupled to the scintillator and photomultiplier tubes, they were secured in place and tested for remaining light leaks which could be sealed with black plastic. The straight, 1S light guide connected to PMT2 remained on one end of the scintillator throughout the experiment and provided a standard against which pulse-height and rise time could be checked. All other light guides were tested on the opposite end with PMT1.

Both pulse height and timing information were recorded. From an oscilloscope, pulse height measurements of noise and minimum ionizing cosmic particles were measured from both tubes. Also, for different apertures, pulse height of signals from both PMTs were determined. The four largest apertures, numbers 6, 7, 8 and 9, were used. By measuring the average pulse height for each aperture and comparing it with the average pulse height of cosmic particles, the apertures were found to be equivalent to 5.08, 6.74, 8.69 and 12.60 MeV respectively. For each aperture, five timing tests, like the one in Figure 2, were done.

Data Analysis

Figures 3a-d show the timing characteristics of the light guides at different apertures. The timing axis here is the counter timing resolution, σ_c , of one light guide timed with the other -- that is, using an average of the signals at both ends of the counter as one STOP signal. The data acquired in our program measured σ_{diff} , the resolution of the time difference between the signals from the two PMTs. In this case, one signal is a START and the other a STOP. To find σ_c , some calculations were necessary.

Each light guide makes its own contribution, σ_{TA} and σ_{TB} , to the timing resolution:

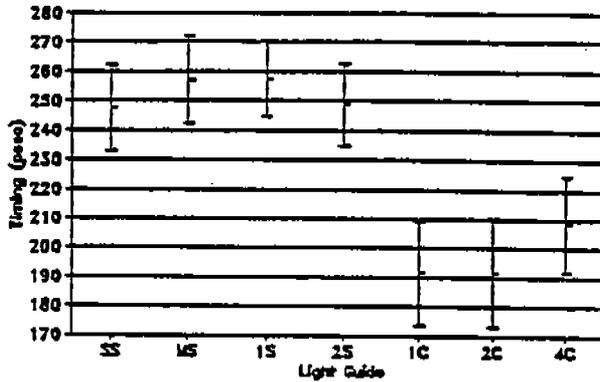
$$\sigma_{diff} = \sqrt{\sigma_{TA}^2 + \sigma_{TB}^2} \quad (1)$$

Thus, if the two light guides were identical, having the same σ_{TA} , then

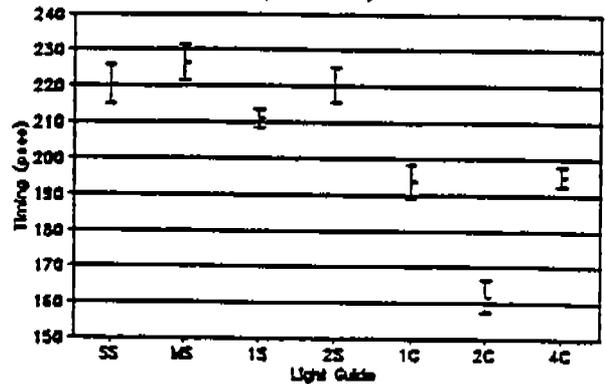
$$\sigma_{diff} = \sqrt{2} \sigma_{TA} \quad (2)$$

One measures σ_{TA} for light guide A by putting two light guides of the same kind on opposite ends and solving for σ_{TA} in equation (2) using the observed σ_{diff} . Then one is able to measure any other light guide's σ_{TB} with the σ_{diff} when the measured light guide A is on one end and the unknown guide B is

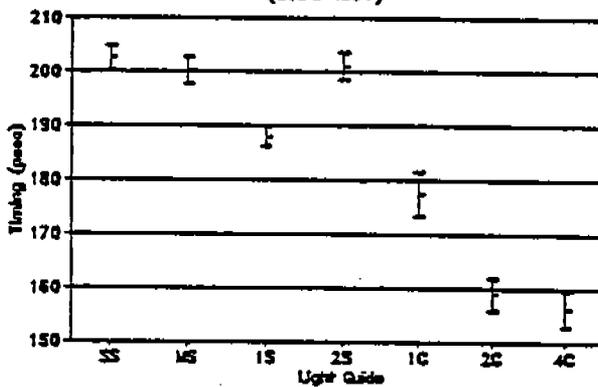
LG Counter Timing at Aperture 6
(5.08 MeV)



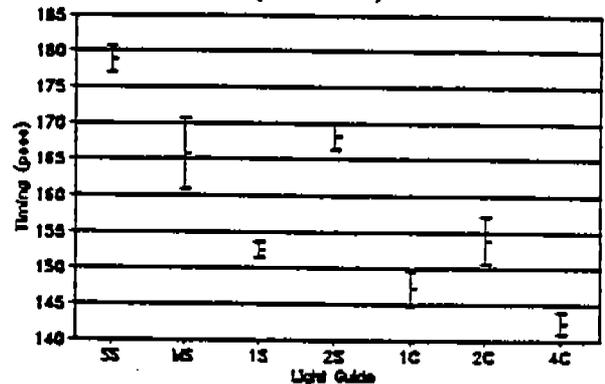
LG Counter Timing at Aperture 7
(6.74 MeV)



LG Counter Timing at Aperture 8
(8.69 MeV)



LG Counter Timing at Aperture 9
(12.60 MeV)



Figures 3a-d. Comparison of Light Guide Counter Timing at four different apertures. Each aperture has a different energy equivalency. All errors are statistical only. Below is a description of each light guide. See Figures 6 and 7 for pictures.

SS - "stubby straight"; 1.75" diameter cylindrical end; total length = 5.25".

MS - "modified straight"; 1.75" dia. end; same body as 1S; total length = 18.25".

1S - "1 piece straight"; 1.5" dia. end; cylinder length = 4"; total length = 19.75".

2S - "2 piece straight"; 1.5" dia. end; cylinder length = 4"; total length = 10".

1C - "1 piece curved"; 2" dia. end with eventual taper to 1.75" dia. at PMT connection.

2C - "2 piece curved"; 2" dia. end.

4C - "4 piece curved"; 2" dia. end.

All light guides are 7.9"(20 cm) wide and 2"(5 cm) thick in order to fit the scintillator.

on the other:

$$\sigma_{TB} = \sqrt{\sigma_{diff}^2 - \sigma_{TA}^2} \quad (3)$$

When the two signals from the PMTs are used together as a counter with the same type of light guide on both ends, then the timing resolution is reduced by a factor of $\sqrt{2}$:

$$\sigma_c = \frac{1}{2} \sqrt{\sigma_{TA}^2 + \sigma_{TB}^2} = \frac{1}{\sqrt{2}} \sigma_T \quad (4)$$

In this experiment, the two straight lucite (1S) light guides were used to find σ_{TA} . The other σ_T s and σ_c s were found using (3) and (4) successively [2].

Table I. Counter timing resolutions at 10 MeV for all the light guides. Note that there was a variety of cylinder couplings to the PMT.

<u>Light Guide</u>	<u>Diameter of Cylindrical End</u>	<u>σ_c at 10 MeV</u>
MC	—————	282.23
1S	1.5 inches	178.01
2S	1.5 inches	181.37
MS	1.75 inches	184.63
SS	1.75 inches	189.34
1C	2 inches*	163.88
2C	2 inches	154.07
4C	2 inches	150.95

* The 1C LG had a 2 inch cylinder on the end, but since it was not long enough to couple to the PMT, we added a cylinder that was tapered to 1.75" diameter at the end that connected to the PMT.

As the timing resolution is related to the inverse of the square root of the energy of the scintillation light, we normalize the data from different apertures so as to obtain a timing measurement at 10 MeV. We assume that, for any timing measurement:

$$\sigma_a = \frac{K}{\sqrt{E_1}}, \quad \sigma_a \sqrt{E_1} = K, \quad (5)$$

where K is a constant. To find σ_c when $E = 10$ MeV, we combine the above equations using data collected and the unknown timing resolution at 10 MeV:

$$\sigma_c(10MeV) = \frac{\sigma_a \sqrt{E_1}}{\sqrt{10MeV}} = \sigma_a \sqrt{\frac{E_1}{10MeV}} \quad (6)$$

An average of these values for the four apertures was taken for each light guide and is displayed in Table 1. Resolutions like 120 psec were only approached for the best light guides. These results show an improvement over previous measurements made here, in which the best resolutions were 250 psec at 13 MeV.

Results and Conclusions

Coupling to the Phototube

Figures 3a-d compare the light guides' timing performance. The graphs show a range within which the actual counter timing of the light guides falls. The range indicated on these graphs, though, only includes statistical error. From our experience in testing light guides, we have found that there are many other sources of error. On numerous occasions during the experiment, it was necessary to readjust the position of the light guide or photomultiplier tube after they were in position because the pulse-height was not optimal. In addition, occasionally it was necessary to move the pulser from its position above the scintillator. The pulse-height from the PMTs was very sensitive to the position of the pulser and the position of 4 mm fiber connecting the pulser and scintillator. Variations in the quality of optical connections – connections between the pulser and the scintillator, between the scintillator and the light guide and between the light guide and the PMT – were our main source of systematic error.

Some additional reproducibility tests were done to quantify these errors. Data was taken both before and after the pulser and a light guide were removed and replaced. When replacing components, we tried to achieve the best possible optical coupling. Analysis of the data shows that our values for σ_c are reliable to within roughly 7 percent. The values in Table 1 were graphed in Figure 4 with the new errors calculated.

The graph shows that the straight light guides, which one would expect to perform the best, did not give results as good as the 2C and 4C light guides

Calculated LG Counter Timing at 10 MeV

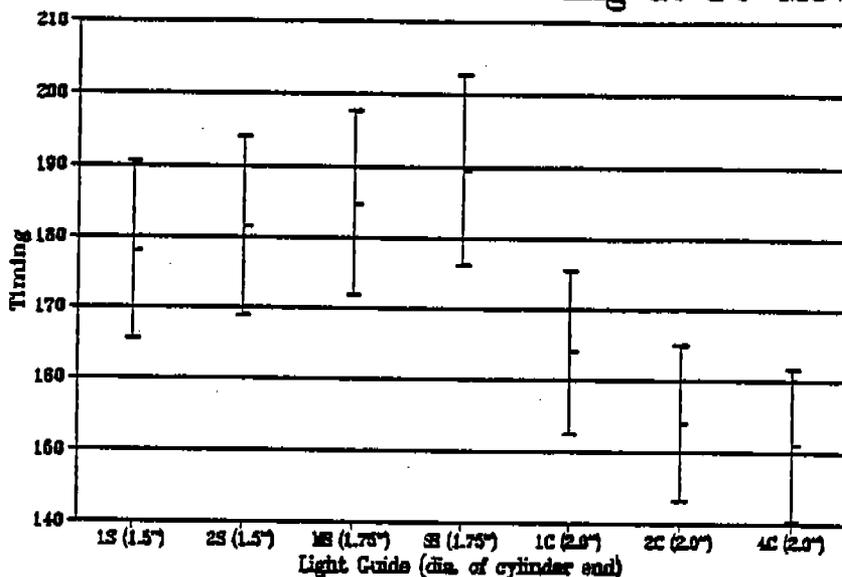


Figure 4. The calculated average counter timing at 10 MeV, the equivalent of minimum ionizing cosmic particles.

that have 2 inch diameter cylindrical ends. The 2C and 4C LGs are significantly better than all the straight light guides. The 1C LG, which also has a 2 inch diameter end, may not be better than the straight LGs because of the taper to 1.75" diameter on the end of its cylinder. It is *not* significantly worse than the 2C and 4C LGs though. If one ignores the MS LG, the mean σ_s for all the straight light guides are in the relative order one would expect. However, because of uncertainties inherent in the experiment, we *cannot* claim significant differences. It seems clear that the effect of different diameters for the cylindrical ends needs to be examined further.

Effects of the Cylinder Diameter

Although the phototubes used in these tests have a nominal diameter of 2", the active, useable area of the photocathode is generally smaller. We have used light guides ending with 1.5", 1.75" and 2" diameter in these tests and have made one test of the possible effects of such variations. The long, straight (1S) light guides were manufactured with 1.5" cylinders (4.5" long) and these were used as the standard throughout these tests. After making the other measurements, we have removed the cylinder supplied with the "standard" light guide at PMT 1 and have replaced that cylinder with a 1.75"

It also seems clear that the 2 and 4 piece curved light guides are better than both the 1 piece guides, both straight and curved. The timing resolutions are consistently 10 - 20 psec lower for the multi-piece curved light guides. The difference here is not as dramatic. One expects poorer performance for the 5 cm thick guide since the ratio of thickness to radius of curvature at the bend is greatest and thus light is less efficiently trapped in the guide.

There appeared to be less difference when the 4 and 2 piece curved light guides were compared against one another. The 4 piece guide was better at aperture 9, and the regions of error overlapped on the other two apertures. Although pulse height was checked (and found to be relatively constant) to insure good optical connections, small, undetectable differences in optical coupling of any of the parts could tend to mask any difference between the two. Thus it would be premature to conclude that the 4 piece light guide is significantly better than the 2 piece one. It is likely that the 2 piece guide will be less expensive to fabricate in large quantities.

In our earliest tests, none of the light guides had adequate timing with the equivalent of 13 MeV deposited by the pulser. This is likely to result from the long rise time of the PMT signal caused by the rise time of the pulser. In subsequent tests we will use more versatile circuitry and data collection methods [5]. Although the goal of 120 psec was not reached for several of these tests, we note that the *relative* timing properties of the light guides were still adequately compared, albeit at higher energies.

dia. by 2.5" long cylinder. We called this modified version of the long, straight light guide the MS light guide. Our expectation had been that the larger diameter would be more efficient. The initial data gathered and shown in Figure 4 and Table 1 shows that the mean counter resolution for the 1S LG is better than that of the MS LG. However, when one takes into account errors other than simply statistical ones – those introduced by contingencies such as the quality of optical connections as discussed above – we see that the results from the two light guides are not significantly different. Before this was discovered, another comparison was done in which the average resolutions differed by even less. Thus, it appears that timing is not affected significantly by whether the light guide has a 1.5" or 1.75" diameter cylindrical end.

We did not compare any light guide with both a 2" diameter end and another diameter end – either 1.5" or 1.75". It would seem, from Figure 4, that the 2" diameter end makes, *at the least*, a slight difference in the timing qualities of a light guide. Unfortunately, the 1S light guide could not accept a 2" diameter end. Further tests will have to be done in the future to determine more exactly the effects of the 1.5", 1.75" and 2" diameter ends.

Light Guides for the Scintillators at Forward Angles in the CLAS

Owing to space constraints in the forward angles of the CLAS, it will probably be necessary to position the photomultiplier tubes and bases in the plane of the scintillators rather than employing the bent light guides described above which remove the tube from the scintillator plane. We have therefore made tests with very short, triangular straight (SS) light guides (see Figure 7). Such guides can be expected to be less efficient at trapping the scintillator light owing to the lack of gradual or "adiabatic" taper from the scintillator end to the phototube position. On the other hand, use of a longer, more tapered pipe in this application would result in the use of shorter scintillators with a consequent reduction in the efficiency and solid angle of the TOF scintillator system. The results of these tests show that the SS light guide is comparable to the other straight light guides (Figure 4).

It is interesting to note the differences in collection of light from different places on the scintillator by the light guide. A radioactive Sr-90 source placed along the edge of the scintillator served as a standard source for scintillation. As the source was placed closer to the light guide, the effective cross sectional area subtended by the circular end of the light guide decreased and pulse height from the PMT consequently decreased. The least pulse height was found to be in the corners of the scintillator. For such corners to be effective area in the TOF system, the discriminators of the PMT signals must have a dynamic range of at least three (See Figures 5a-b).

Pulse Height vs. Horizontal Distance to Start of LG Cylinder End

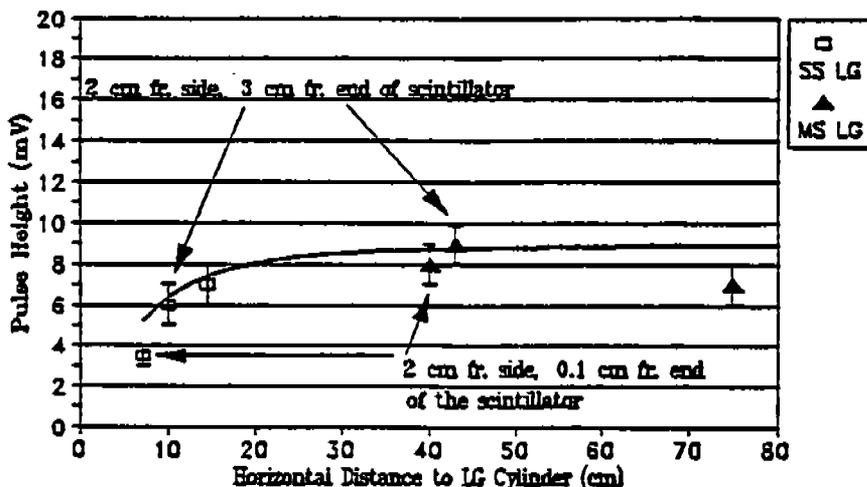


Figure 5a. Pulse Height versus Position on Scintillator.

In the figure, the line is the function $PH = (9 \text{ mV}) \cos \theta$. The two points which are the same on the scintillator are both 2 cm from the side of the scintillator. One point is at the very end of the scintillator; the other is 3 cm from the end of the scintillator, as in Figure 5b. The MS and SS light guides have different lengths - 40 cm and 7.1 cm, respectively.

The curve is only "expected" if pulse-height is directly related to the effective area of the end of the cylinder. Because of reflection and solid angle considerations this is not perfectly accurate. Nevertheless, it can be seen that the pulse-height from light originating in the corner of the scintillator is less than optimal for the SS LG. Since pulse-height from light originating in the middle of the scintillator is three times the pulse-height in the corner, the discriminators connected to the PMTs on any SS LG must have a dynamic range of three or better.

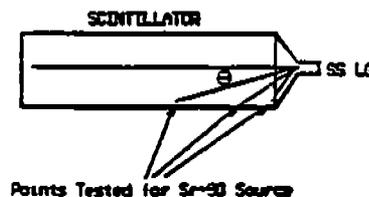


Figure 5b. As the source is placed further from the end of the scintillator, the effective area of the end of the cylinder increases as $\cos \theta$.

Several conclusions can be drawn from the data. First, it is clear from previous work that the reflective mirrored air light guide is not competitive with the lucite light guides. Pulse height from the PMT connected to this guide was extremely low perhaps because of poor reflection of the light by the metal and reflection of the light back into the scintillator or because of absorption of some of the light by the aluminum. It is worth noting that this type of light guide could undoubtedly be improved by use of the Winston Cone shape [4]. The air guide's shape was clearly not optimized for non-imaging optics [4]. Consequently, timing resolution was roughly 100 psec worse than the straight light guides.

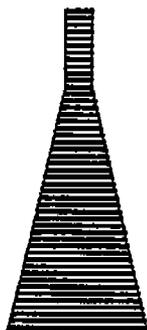
It also seems that the 2 inch diameter cylindrical end gives the 2 and 4 piece curved light guides an advantage over the straight guides. It is difficult to compare the 1 piece curved light guide to either the straight light guides or the multi-piece curved light guides because of the uncertainty in the quality of optical connections. One expects poorer performance for the 5 cm thick guide (compared to the 2 or 4 thinner pieces in the 2C and 4C LGs) since the ratio of thickness to radius of curvature at the bend is larger and thus light is less efficiently trapped in the guide. It would be premature to conclude that the 4 piece light guide is significantly better than the 2 piece one. It is likely that the 2 piece guide will be less expensive to fabricate in large quantities if curved light guides are needed. The difference between all the light guides, save the mirrored air guide, is not very dramatic. More work definitely needs to be done when the cylinder diameter is standardized and possibly when the optical connections can be made uniformly and optimally.

Where short light guides are needed at forward angles in CLAS, it seems that the fact that they do not have a gradual taper may not have a significant effect of counter timing. We do know that for the corners of the scintillator to be effective solid angle in CLAS, because of decrease pulse-height from these areas, the discriminators must have a dynamic range of three or more.

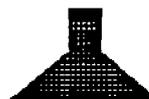
In our earliest tests, none of the light guides had adequate timing with the equivalent of 13 MeV deposited by the pulser. This is likely the result of the long rise time of the PMT signal caused by the rise time of the pulser. In these tests we have used more versatile circuitry and data collection methods [5]. Although the goal of 120 psec has not yet been reached for these tests, by decreasing the rise time of the pulser, we have decreased counter timing to 55 percent of those in the previous tests. In doing so, the differences among the light guides have been made smaller. Thus the counter timings measurements in these most recent test are more accurate reflections of the light guides' timing characteristics.

We thank M. Eckhause, W. R. Hall, A. D. Hancock, and R. G. Winter for assistance and suggestions. We are most grateful to J. Bense, K. Jacobs and M. Woods of the William and Mary Physics machine Shop for precise fabrication of the light guides and other materials.

A. 1S Light Guide



C. SS Light Guide



B. Cylindrical End for
MS Light Guide



D. 2S Light Guide

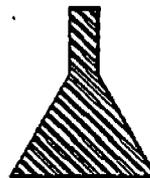


Figure 6. Diagram of the straight light guides. Dimensions of the light guides may be found below Figures 3a-d.

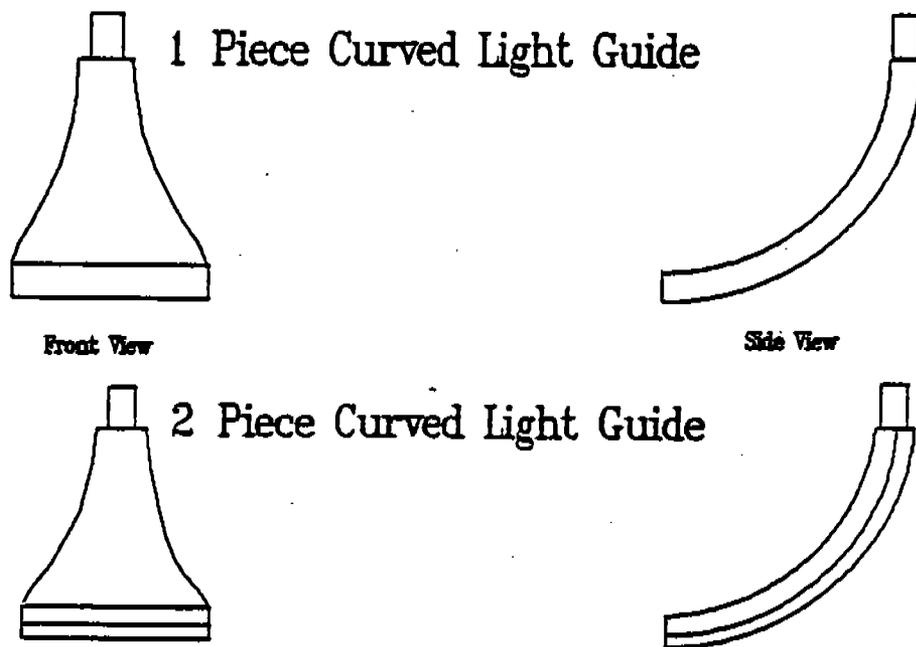


Figure 7. Diagrams of the one piece and two piece curved light guides.

References

- [1] "Conceptual Design Report - Basic Experimental Equipment," CEBAF, April 13, 1990.
- [2] C. Hoff *et al.*, "Design and Testing of Light Guides for the CLAS Detector," CLAS-NOTE-90-016, December 4, 1990.
- [3] Fabricated for this research by Chas Nichols, CERN, Geneva. See also Hamamatsu Catalog "Light Sources," November, 1989.
- [4] R. Winston, "Nonimaging Optics," *Scientific American*, pp. 76-81, March 1991.
- [5] G. D'Agostini *et al.*, "Time-of-Flight Resolution for a Long Scintillator Counter," *Nucl. Instr. and Meth.*, 219 (1984) 495.