CLAS Large Angle Time Of Flight Light Guides

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1) Introduction

As mentioned in a previous report[1], given a certain photocathode area, the timing resolution for the CLAS large angle TOF scintillators is mainly determined by the optics of the scintillators and light guides. This report gives the results of Monte Carlo modeling of several optic geometries (Sections 2-10) using a modified version[2] of the code GUIDE7 [3]. Section 11 gives possible solutions for promising light guide geometries.

All calculations are done with zero absorption of the scintillator material and infinitely fast scintillator response on a 20 x 5 cm^2 cross section scintillator (4 to 1 aspect ratio). Most light guides simulated provide an output aperture of 33 cm^2, comparable to that of a 3" PMT. The scintillator and light guides have an index of refraction of 1.5. 10.000 Photons are generated along a line perpendicular to the large surface of the scintillator. The critical angle is 47 degrees relative to the scintillator surface. No polarization effects are taken into account. For the coordinate system see Figure 5. Angles are measured relative to z, which is along the length of the scintillator. The thickness is in the y direction, and the coordinate x is along the width of the scintillator.

The goal is to design a light guide that optimizes the timing characteristics of the counter. We therefore attempt to maximize the light collection of prompt photons, that is, those contributing to the first few nanoseconds of the PMT signal.

2) Total light output of scintillator

To compare the light output and time distribution of different light collectors, we first calculate the total light output at the ends of the scintillator. Figures 1-4 show the arrival time distribution and intensity of light generated at 15, 115, 215 and 315 cm (referred to as source distance) respectively from the end of the scintillator. The dispersion due to multiple reflections for longer source distances is clearly visible. The 215 cm case also shows emission angles (relative to z) on the time axis for later reference.

Emission angle and arrival time appear closely related even with rectangular scintillators with larger aspect ratio. This appears to be a general feature of a straight scintillator with arbitrary cross section[5].

The histograms are cutoff around 30 ns by software to limit excessive CPU time. The length of the scintillator does not determine the maximum arrival time, because light can be emitted at an angle close to 90 degrees relative to z and still undergo total internal reflection around 45 degrees relative to the scintillator surface. Thus very long travel times are possible, with the light following a left or right turning corkscrew-like path around z.

Also note that the total amount of light coming out of the end of the scintillator does not depend on the source distance, since the coefficient of absorption of the scintillatior material is set to zero.

3) Minimum configuration: the cylindrical light guide.

When a 3" PMT is attached to the end of the scintillator via a short cylindrical light guide (7 cm long to allow magnetic shielding for the PMT), most light is lost because of the small PMT cathode surface relative to the (20 x 5 cm^2) scintillator cross section. Figure 5 shows the output of this minimum configuration with a source distance of 215 cm. Compared to Figure 3, over 70% of the amplitude of the signal is lost, while the time distribution is similar.

4) Light collection of Winston cone

The most effective shape of a light guide is the Winston cone [4]. The code GUIDE7 was modified to allow the Winston geometry. A Winston collector will accept all light that enters at an angle smaller than the maximum angle θ_{max}, characteristic for that Winston collector. Consequently we expect the distribution shown in Figure 3, cut off at θ_{max} without affecting the height, when a Winston collector is attached to the scintillator. This is approximately what is observed.

It should be noted that Winston defined his geometry only in two dimensions. Often, the extension to the 3-d case is obtained by rotating the 2-d cone around its symmetry axis, which is not attempted here due to the lack of azimuthal symmetry. The 3-d geometry simulated here is created by using 2-d geometries independently for x and y. The extension to a 3-d geometry is not backed by any mathematical formalism. However, light rays propagated through this geometry also show a sharp cutoff close to θ_{max} as defined in the 2-d case. Figure 6 shows the output of a Winston geometry with θ_{max} = 33 degrees in both the x and y directions (output aperture: 11.49 x 2.87 cm^2). The length of the collector (22.5 cm) is determined by the surface areas of the PMT cathode and the scintillator cross section (output and input apertures of the collector). Because different lengths are required for the x and y Winston collectors, the collector in the y direction must be extended by a flat section to compensate for the longer length of the x collector. Alternatively, a Winston collector can be defined with the same x and y lengths (Section 10), but will result in different maximum angles for the x and y directions. By design, the output aperture of this collector will match the area of the PMT. However, the aperture shape is rectangular, so in practice this collector must be followed by an adiabatic light guide to connect the guide to the PMT photocathode. In the modeling that follows we add a rectangular piece to the end of the Winston collector to simulate the effect of this additional adiabatic collector, although the actual twisting of the pieces of an actual guide is not simulated.

5) Light collection of fishtail

A regular fishtail light guide is tapered only in the x direction with an output aperture that matches the PMT cathode surface. After the cylindrical guide this is the most simple and common type of light guide. Figure 7 shows the response of a 38 cm long fishtail. The performance is clearly inferior to the much shorter Winston collector of Figure 6.

6) Light collection of two-dimensional fishtail with Winston apertures

To simplify the Winston collector approach of Figure 6, its curved surfaces are replaced with straight ones to evaluate the loss of signal caused by this simplification. Figure 8 shows the result if only the Winston surface curved in the y-direction (including the part parallel to z) is replaced by a straight taper. In Figure 9 both the x and y surfaces are replaced by planes (source distance: 215 cm). Considering its much simpler shape this two-dimensional fishtail appears an attractive alternative to the Winston collector.

7) Light collection of 2-d fishtail with final straight section

The light guides described in the above sections are expected to be followed by the photo cathode of a PMT. However, often a final straight section is needed to allow for a magnetic shielding or to displace the PMT. Figure 10 shows the light loss caused by an 8 cm long straight section attached to the 2-d fishtail configuration of Figure 9.

8) Light collection of 2-d fishtail with unequal lengths

Because the y-dimension of the scintillator is smaller than the x dimension, the tapered surface in the y-direction can be shorter than that in the x-direction. Figures 11, 12 and 13 show 40 cm long fishtail light guides that have 5, 10 and 40 cm long tapered surfaces in the y direction, and a fixed 40 cm long taper in the x direction. In the 5 (10) cm cases there is no tapering in y-direction for the last 35 (40) cm of the guide. Only for very short tapers we find a significant light loss. Note that, as in Section 7, there is an 8 cm long straight section added to the end of the light guide.

9) Light collection of 2-d fishtails with different output apertures

To check how optimal the aspect ratio of the output aperture (11.49 x 2.87 cm^2) determined by Winston's relations is, the ratio was varied, while keeping the surface area constant for the adiabatic coupling of a 3" PMT. Figures 14 to 19 show the output of 6 different aspect ratios of 2-d fishtail light guides. Figures 14 and 19 are actually one dimensional fishtails (Section 5). Figure 17's aspect ratio (12.7 x 2.6 cm^2) is similar to that determined by the Winston conditions and the light intensity distribution appears close to optimal.

10) Light collection of 45 degree reflector with Winston collector

A special kind of guide was simulated to verify the results of a prototype[5)] with a two dimensional Winston collector mounted at 45 degrees relative to the scintillator axis. θ_{max}'s in the x and y directions are different: $\theta_{max}(x) = 49$ degrees; $\theta_{max}(y) = 11.4$ degrees. The lengths (22 cm) are the same. The response is shown in Figure 20. It was anticipated that there is more light emitted per degree around 45 degrees relative to the scintillator axis than at smaller emission angles (see the angle scale in Figure 3 to get an idea about photons per degree). However, the arrival time spread is wide and light is lost at the interface to the air filled collector. Figure 21 shows a histogram of locations where the light loss occurs as a function of z.

11) Conclusions and possible solutions for the CLAS large angle TOF system

As far as collection efficiency and time spread of the different light guides is concerned, the Winston shape collects more light in less space than other shapes do. It collects about three times more light at angles below θ_{max} than the cylindrical guide of Section 2. For a typical maximum angle θ_{max} = 33 degrees, the light output is concentrated in a 3 ns interval (Section 4). This is similar to the PMT minimum pulse width and to dispersion by the scintillation processes. Assuming, that light arriving beyond 3 ns does not significantly contribute to the time resolution of the scintillator/PMT combination,[1] the Winston collector with a 3" PMT is as good as a hypothetical super PMT that would cover the full 20 x 5 cm^2 cross section (results of which are shown in Section 2).

When the Winston surfaces are replaced by planes or a straight section is added to the end, there is only a slight loss of performance (Sections 6 & 7). In these straight, tapered sections, it is not the slope that determines the maximum angle that the guide accepts, but rather the reduction in size of the optical system that results from the taper (Section 8). This is analogous to Winston cones, where this size reduction determines θ_{max} directly. It also determines the length of the cone. A straight taper with this length has a slightly less clear defined maximum angle. Increasing the length of the taper, while keeping the size reduction fixed, gives an angular distribution very close to that of the (shorter)

[1] To verify this, the calculated responses have to be convoluted with the PMT response function. The resulting pulse height is approximately proportional to the square of the timing resolution.

Winston cone (Section 8). Even longer, straight tapers however will result in increased dispersion due to multiple reflections, like in the case of large source distance (Section 2).

For the large angle CLAS TOF system, there is only 30 cm along the z axis available for light guides if the PMT axis is aligned with that of the scintillator. This is probably not sufficient for even the minimum configuration (Section 3), thus a bent guide is needed, in addition to a collector. To reduce the cross section of the bent guide (thick Lucite is hard to deform), the collector should precede the bent guide. However this is difficult because of the restricted space. Because the length of the collector in the y-direction is much shorter than that in the x-direction, a short fishtail for the y-dimension can precede the bent guide, reducing the thickness of the Lucite to be bent. The curved -- or straight-- collector in the x direction can be incorporated in the bent guide.

To get the simulated performance, an additional adiabatic guide is needed to match the shape of the PMT cathode to the output aperture of the guide. However, this can also be built into the bent guide if we cut it in many strips of smaller cross section. A simplification of this is to use only a few strips, that can be twisted and form an adiabatic geometry. Thus the bent guide combines three functions: displacing the PMT, full light collection within an angular range, and adiabatic transmission.

Figures 22, 23 and 24 show possible configurations as described above, with different scintillator widths and PMT diameters. The difference between the three configurations is the number of strips that make up the bent part of the guide.

With 3 strips of bent light guide, the scintillator thickness fixed at 5 cm and a 10 x 10 cm^2 (5" PMT) output aperture, all essential parts of the geometry are determined by Winston's relations (requiring that the size reduction is the same in both the x and y directions), and the scintillator will need to be 45 cm wide. The maximum angle is 42 degrees (Figure 22). This configuration collects more light than the other two and is expected to have the best time resolution also. However, the extra light is added to the trailing edge of the signal and the resulting improvement in resolution is probably small.

With 4 strips of bent guide and a 5" PMT, the scintillator needs to be 80 cm wide and accept light inside a 30 degree cone (Figure 23). This is the lowest cost configuration, because off the small number of PMT's needed to cover the large angle part of CLAS and the small number of scintillators to be assembled. However the 80 cm width of the units will make them very heavy and hard to handle.

With 2 strips of bent guide, a 3" PMT can be used (5.5 x 5.5 cm^2 output aperture) resulting in a 20 cm wide scintillator with θ_{max}.= 33 degrees (Figure 24). This is the proposed configuration with lower cost light guides and PMT's (one half that of 5" tubes) and relatively light scintillator units that can be lifted by two persons. The taper in the strips has been extended over the full length for easier manufacturing and a slightly better angular definition (Section 8).

As a conclusion we can say that perfect Winston collectors and perfect adiabatic guides give a factor 3 improvement over the minimum configuration of cylindrical guides by collecting all light conducted by the scintillator in the first few nanoseconds for 3" PMT's and 20 x 5 cm^2 scintillators. Either of the three proposed, simplified configurations should produce at least twice (allowing for some losses due to imperfections in the adiabatic part) the light output of the cylindrical guide, improving the time resolution by a factor of 1.5.

References:

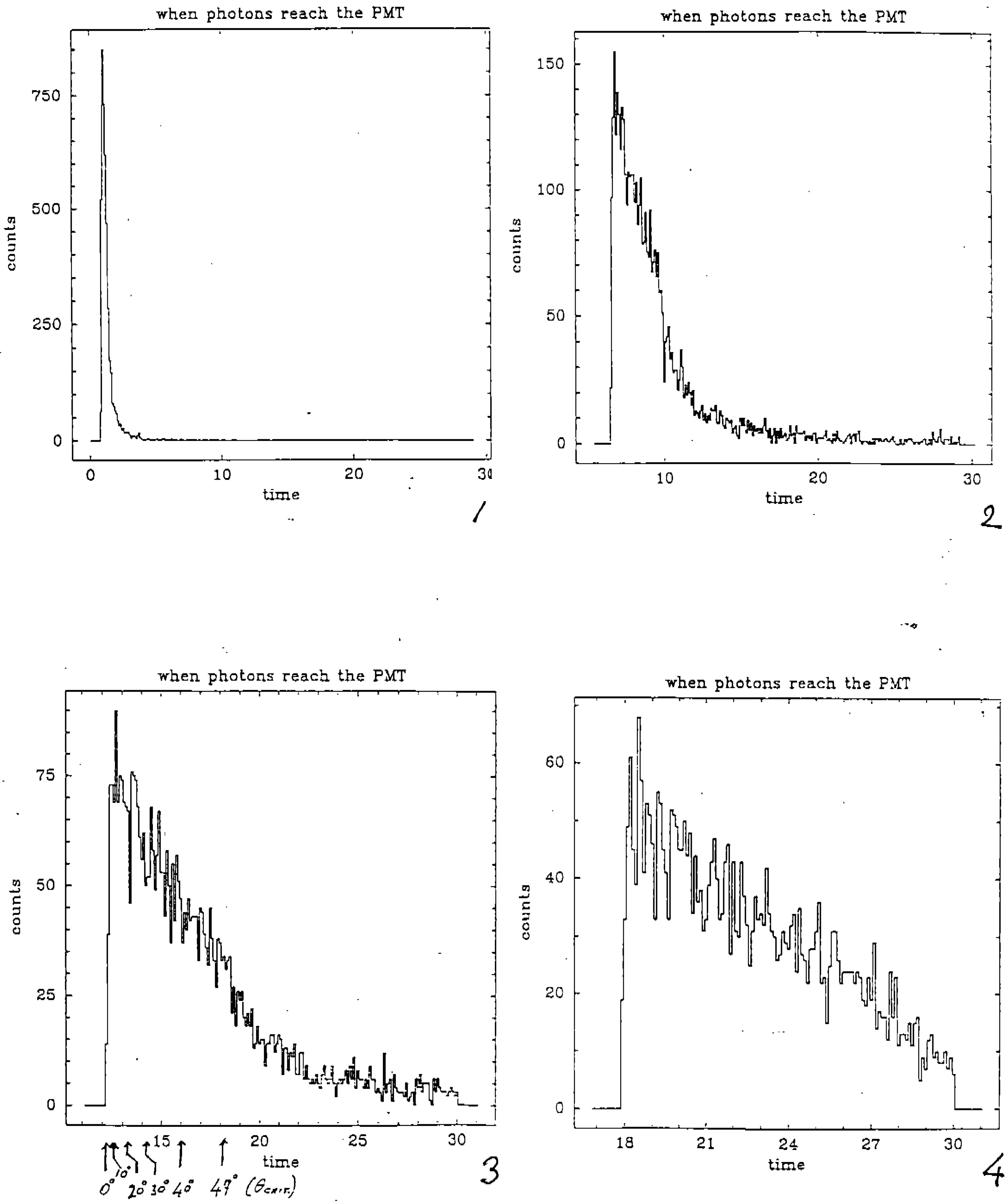
1) E.S. Smith, et.al., "Tests of 3" Photomultiplier Tubes for CLAS TOF", CLAS-NOTE-015, September 16,1993.

2) T.Smith and J.Distelbrink, 3-dimensional graphical output procedure "SHOW"; modified GUIDE7 with capability to accept 2-dimensional Winston geometries: "WIN7".

3) "GUIDE7 , A General Program for Evaluating the Properties of Scintillation and Cherenkov Counter Optical Systems", E. Massam, March 23 1977, Experimental Physics Division CERN.

4) H. Hinterberger and R. Winston, "Efficient Light Coupler for Threshold Cherenkov Counters", Rev. Scient. Inst. 37,1094 (1966).

5) E. Smith, "Winston Cone Geometries", internal communication.



Figures 1-4. Total light output and arrival time distributions for the standard scintillator with the source at 15, 115, 215 and 315 cm from the end respectively.

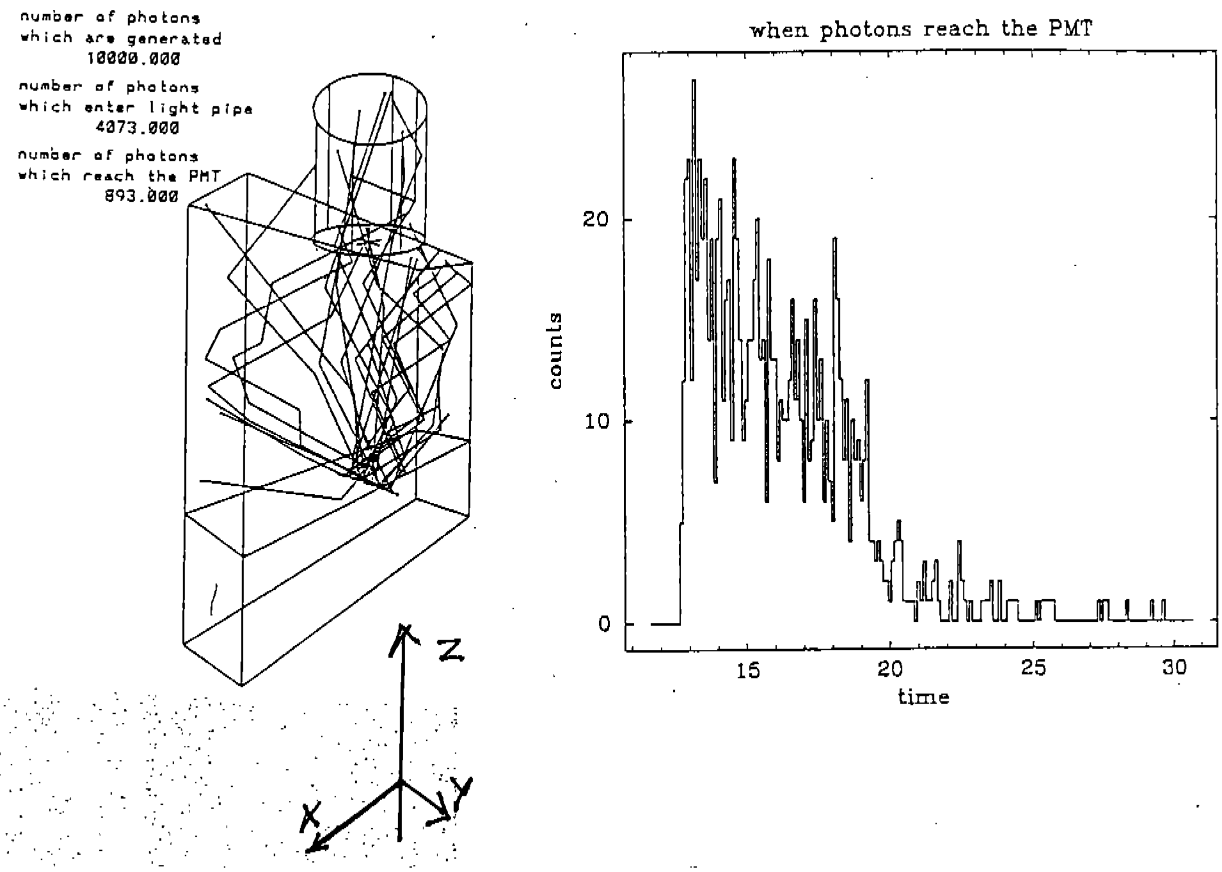


Figure 5. **Output of a 3" diameter, 7 cm long cylindrical guide attached to the standard scintillator. Source distance: 215 cm from end of scintillator.**

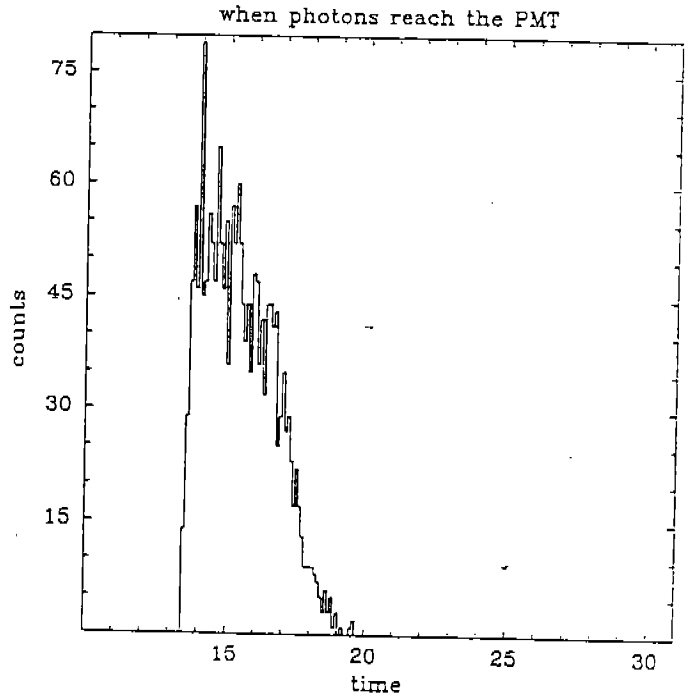


Figure 6. Output of a 33 degrees, 22.5 cm long, two-dimensional Winston collector attached to the standard scintillator.

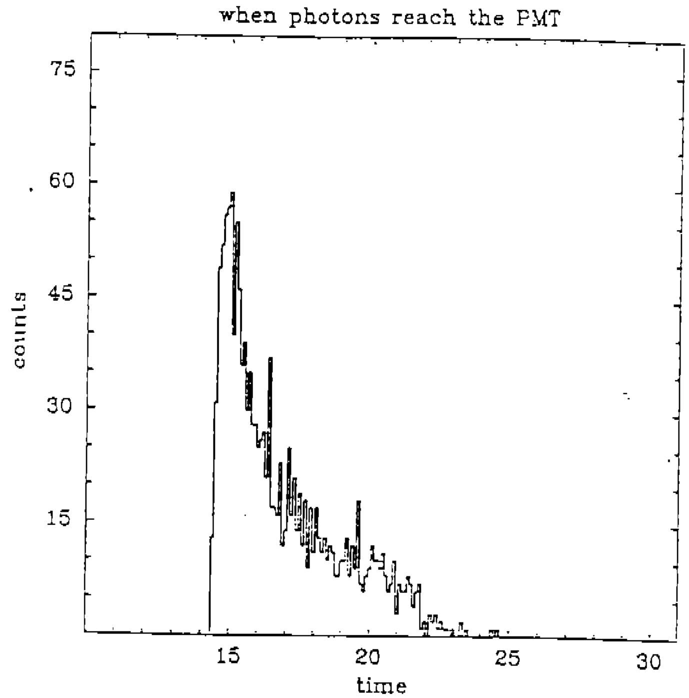


Figure 7. Output of a 38 cm long one-dimensional fishtail. Source distance: 215 cm from the end of the scintillator.

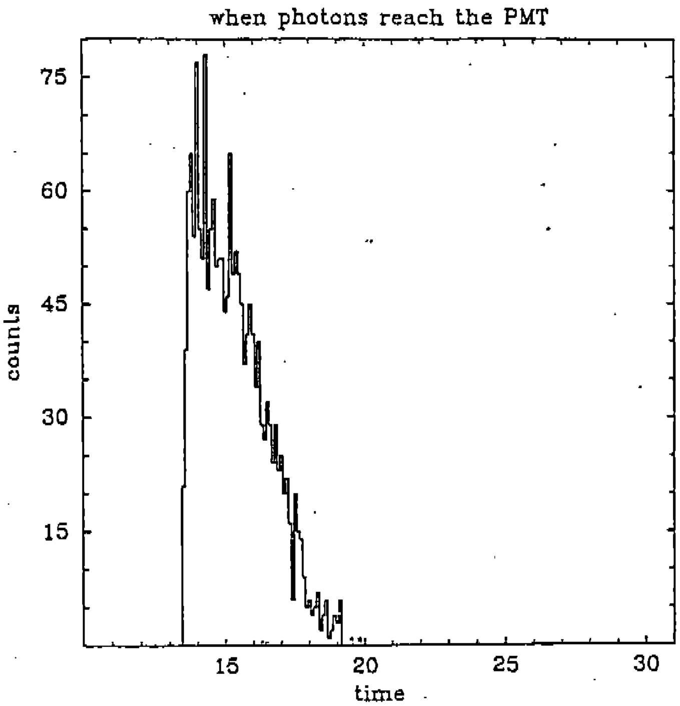


Figure 8. **Winston collector as figure 6, with one surface replaced by plane.**

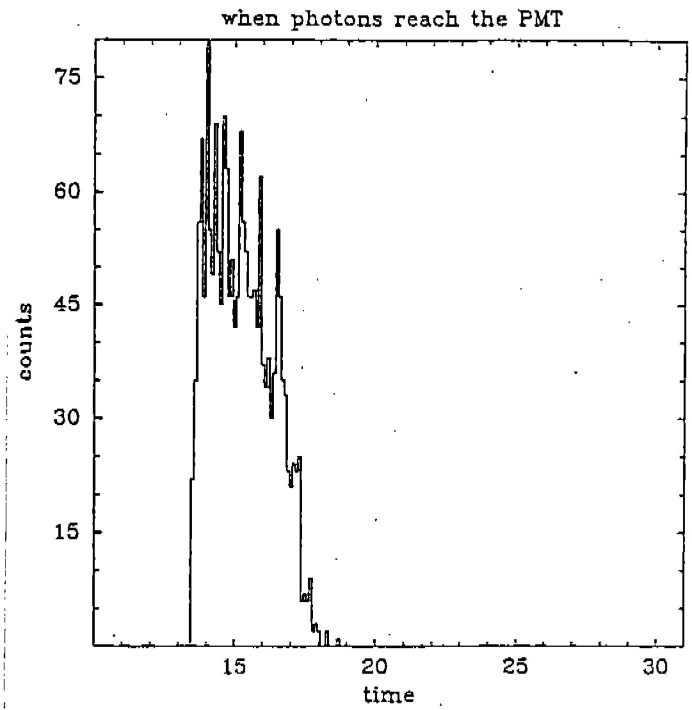


Figure 9. **Both curved surfaces replaced by planes (22.5 cm fishtail).**

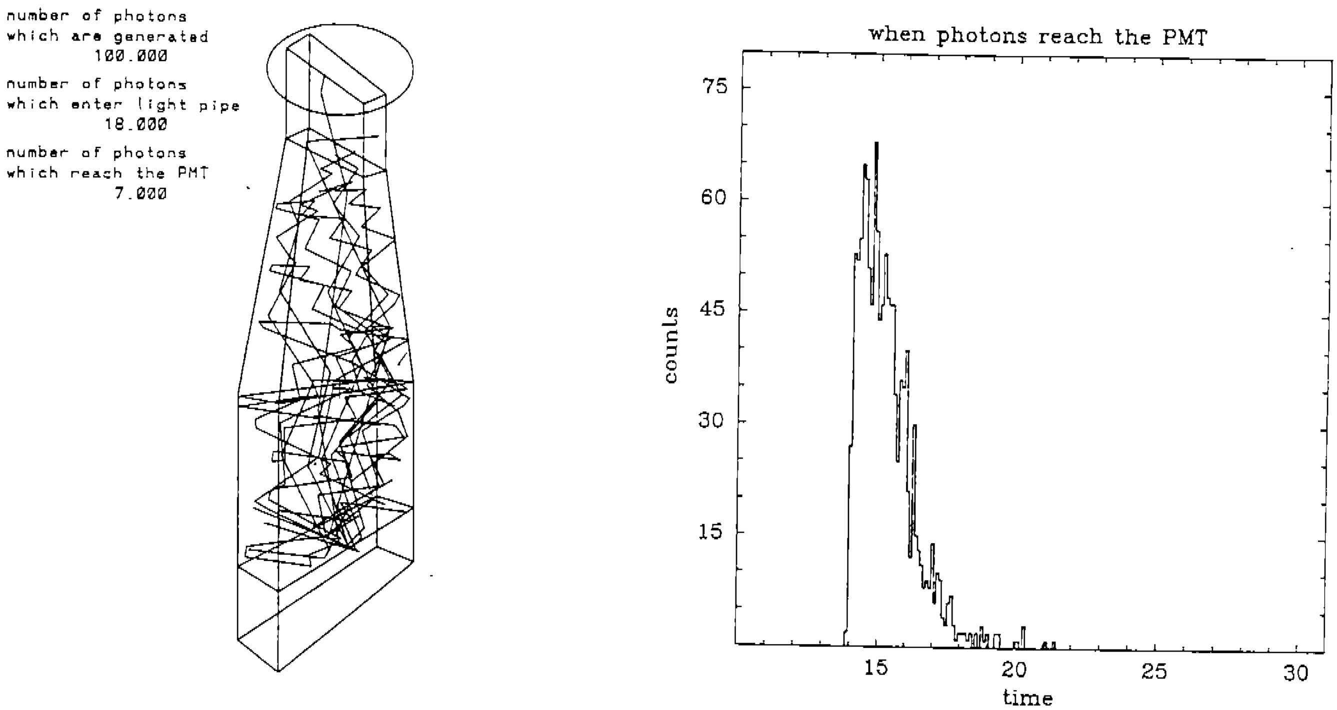
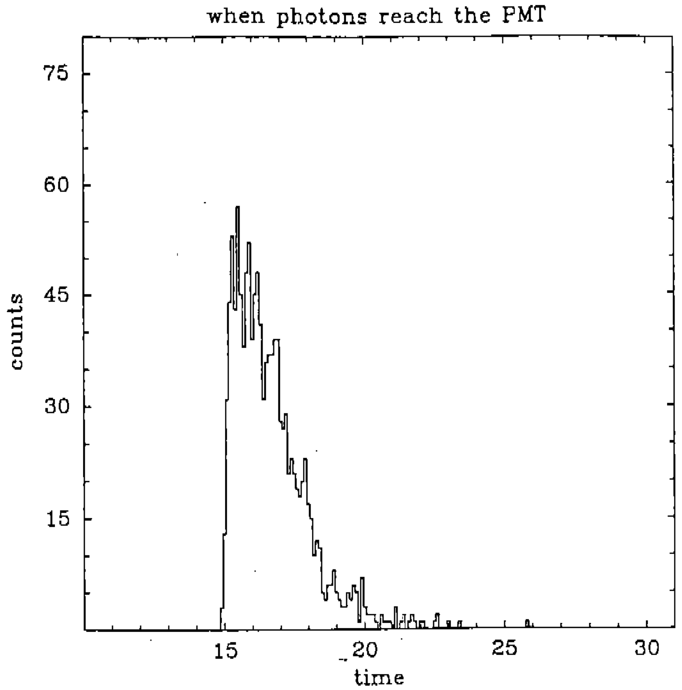


Figure 10. As figure 9, but with 8 cm long straight section added.



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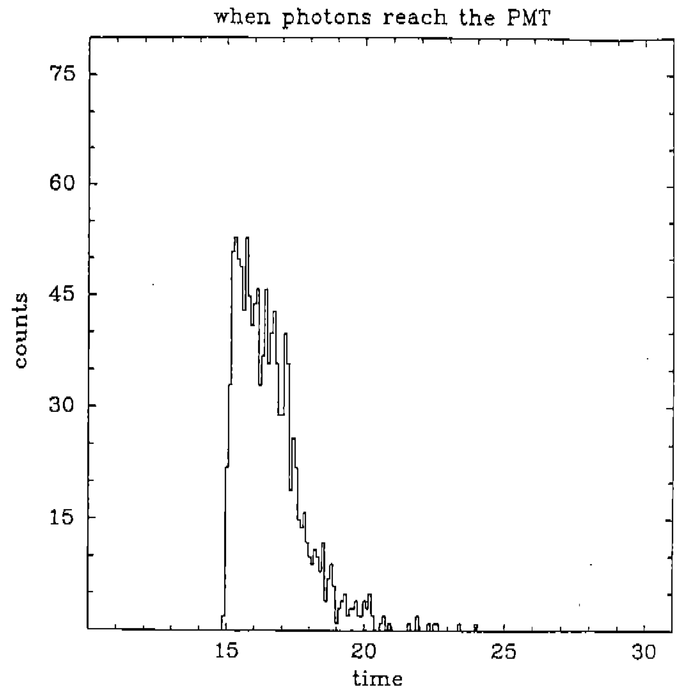

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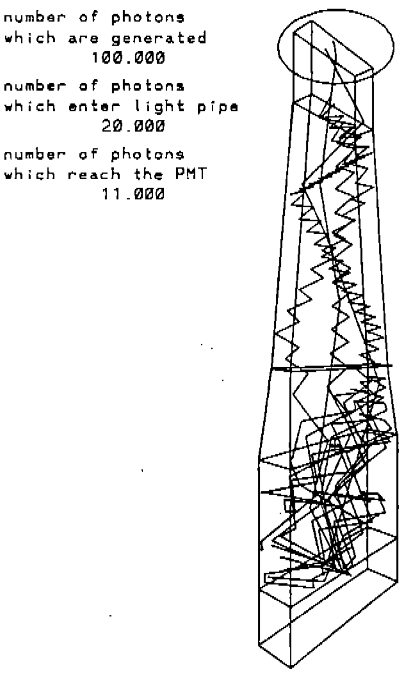

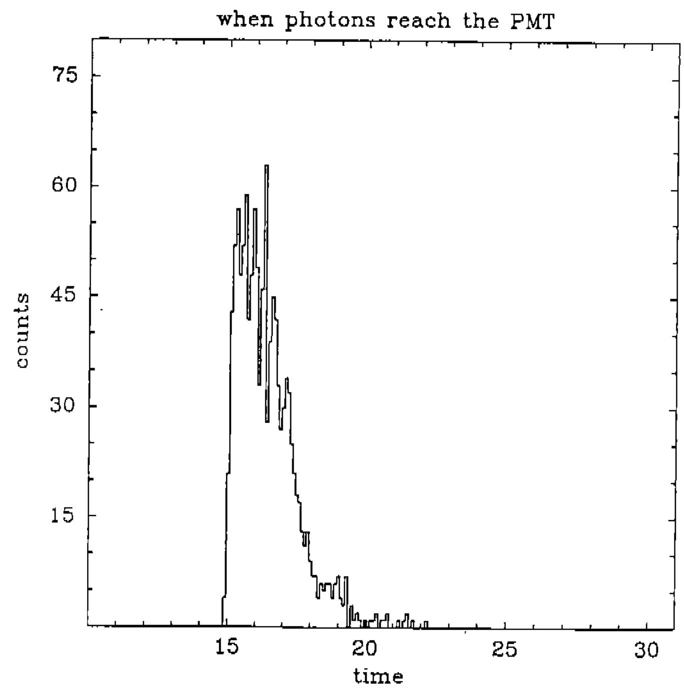

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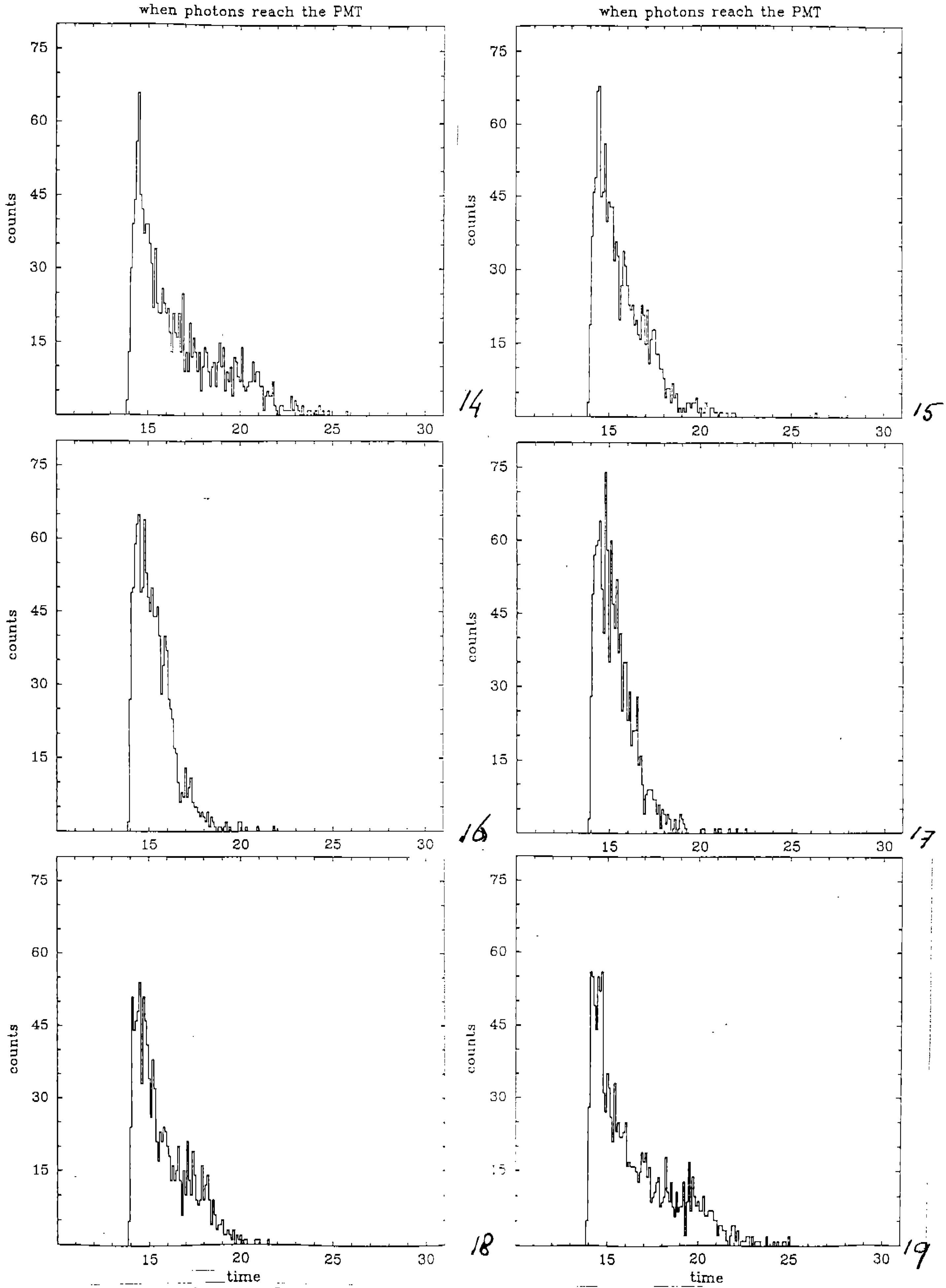
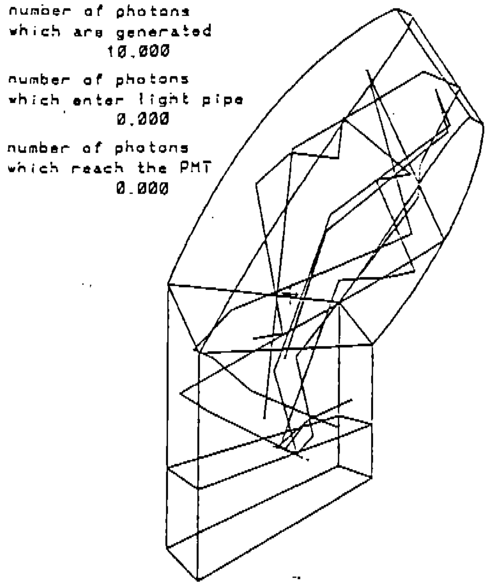
Figures 11,12 and 13. **40 cm long two-dimensional fishtail, with the one in y-direction only 5, 10 and 40 cm long respectively.**



Figures 14-19. **Outputs of a 22.5 cm fishtail with 33 cm² output aperture and varying aspect ratios: 5 = 6.6, 4 = 8.25, 3 = 11, 2.6 = 12.7, 2 = 16.5**



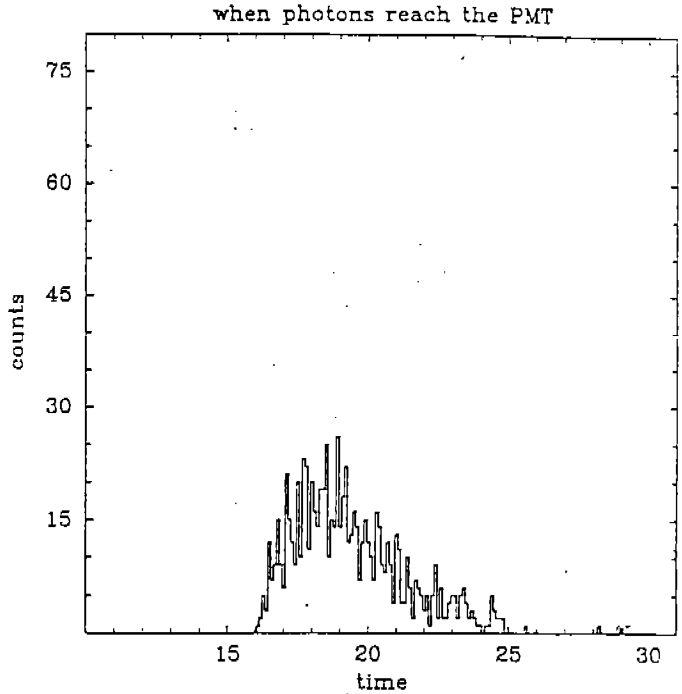


Figure 20. **Two dimensional Winston collector mounted at an angle of 45 degrees relative to the scintillator axis.**

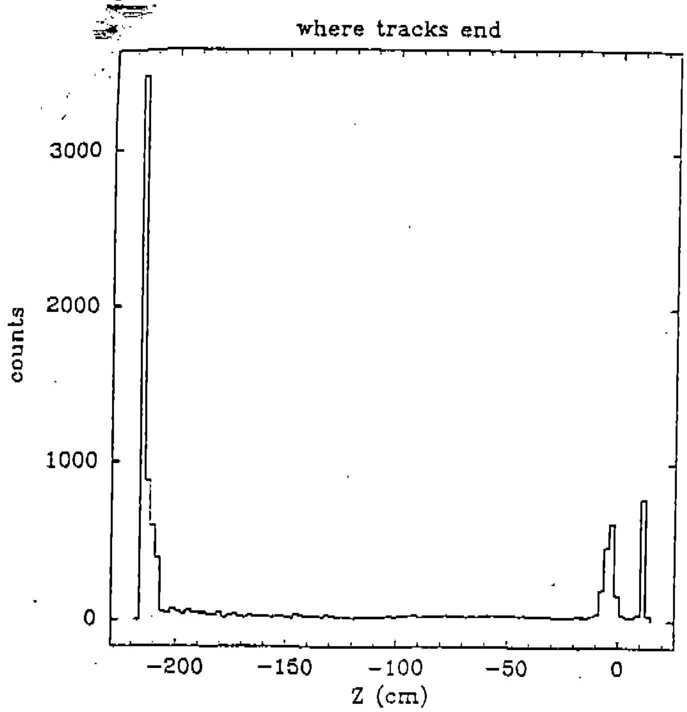


Figure 21. **Light losses as a function of z.**

45 cm Large Angle TOF Scintillator Adiabatic Light Guides (Concept)
Maximum acceptance: 41.8 degrees

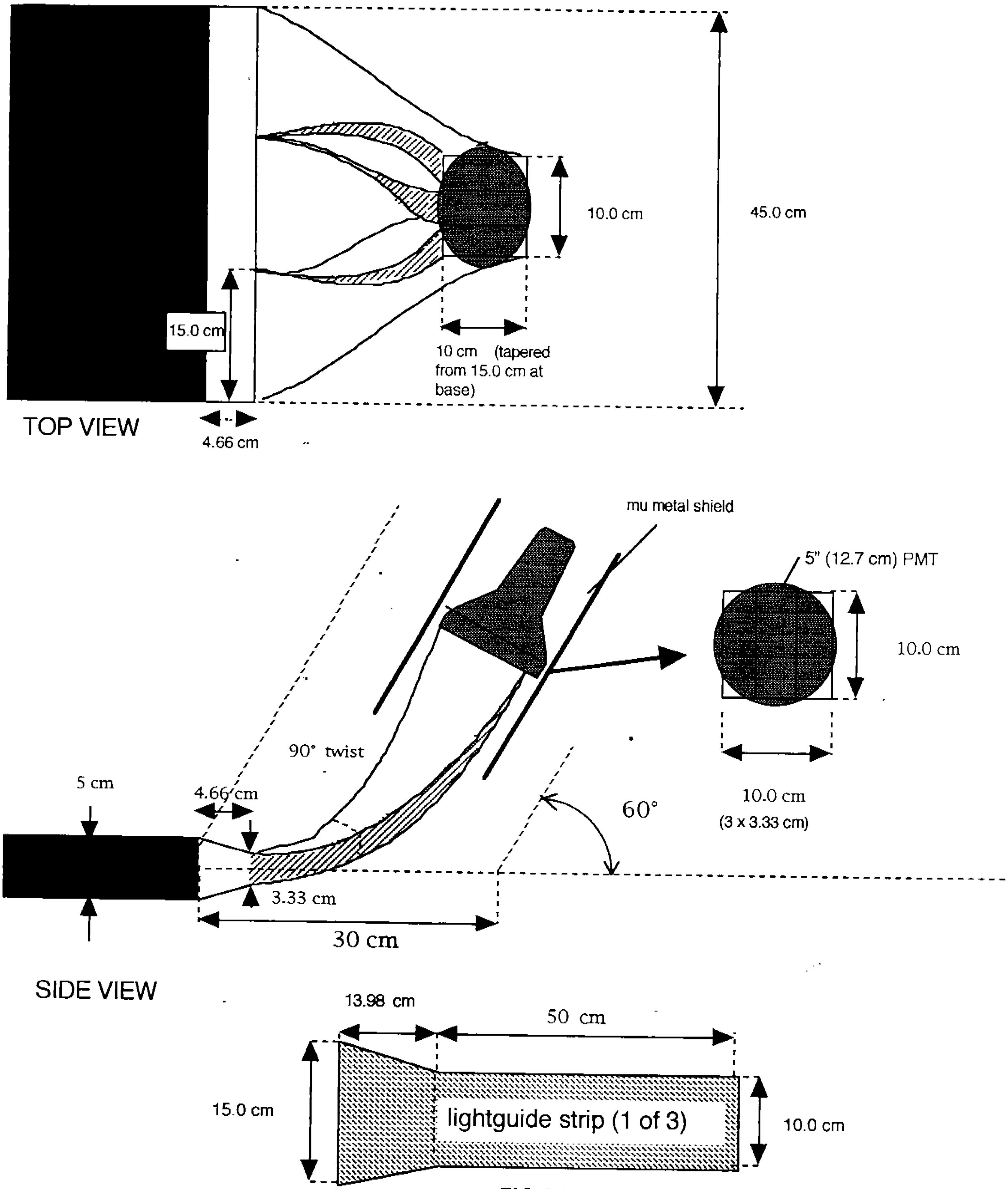


FIGURE 22

80 cm Large Angle TOF Scintillator Adiabatic Light Guides (Concept)
Maximum acceptance: 30.0 degrees

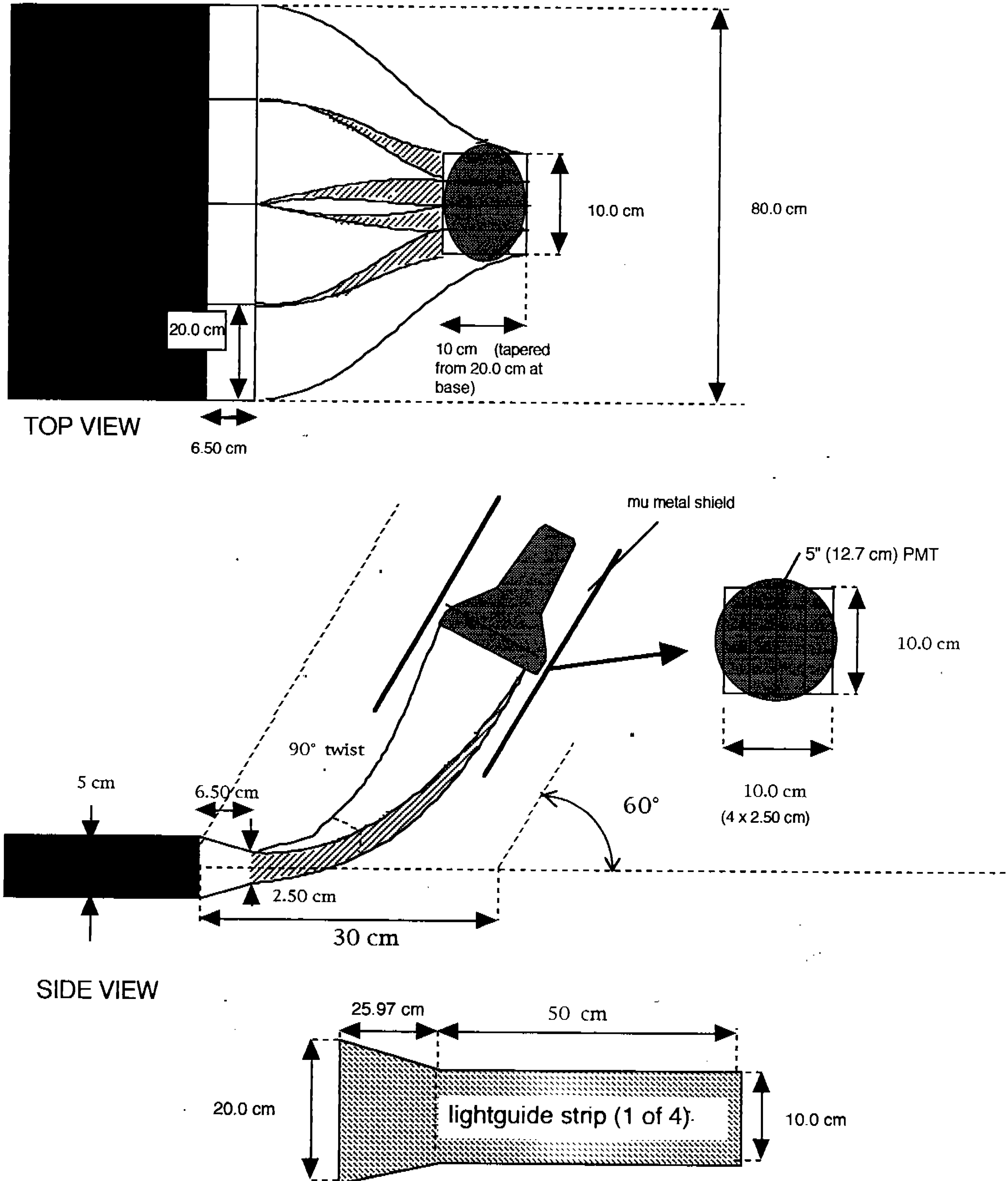


FIGURE 23

20 cm Large Angle TOF Scintillator Adiabatic Light Guides (Concept)
Maximum acceptance: 33.4 degrees

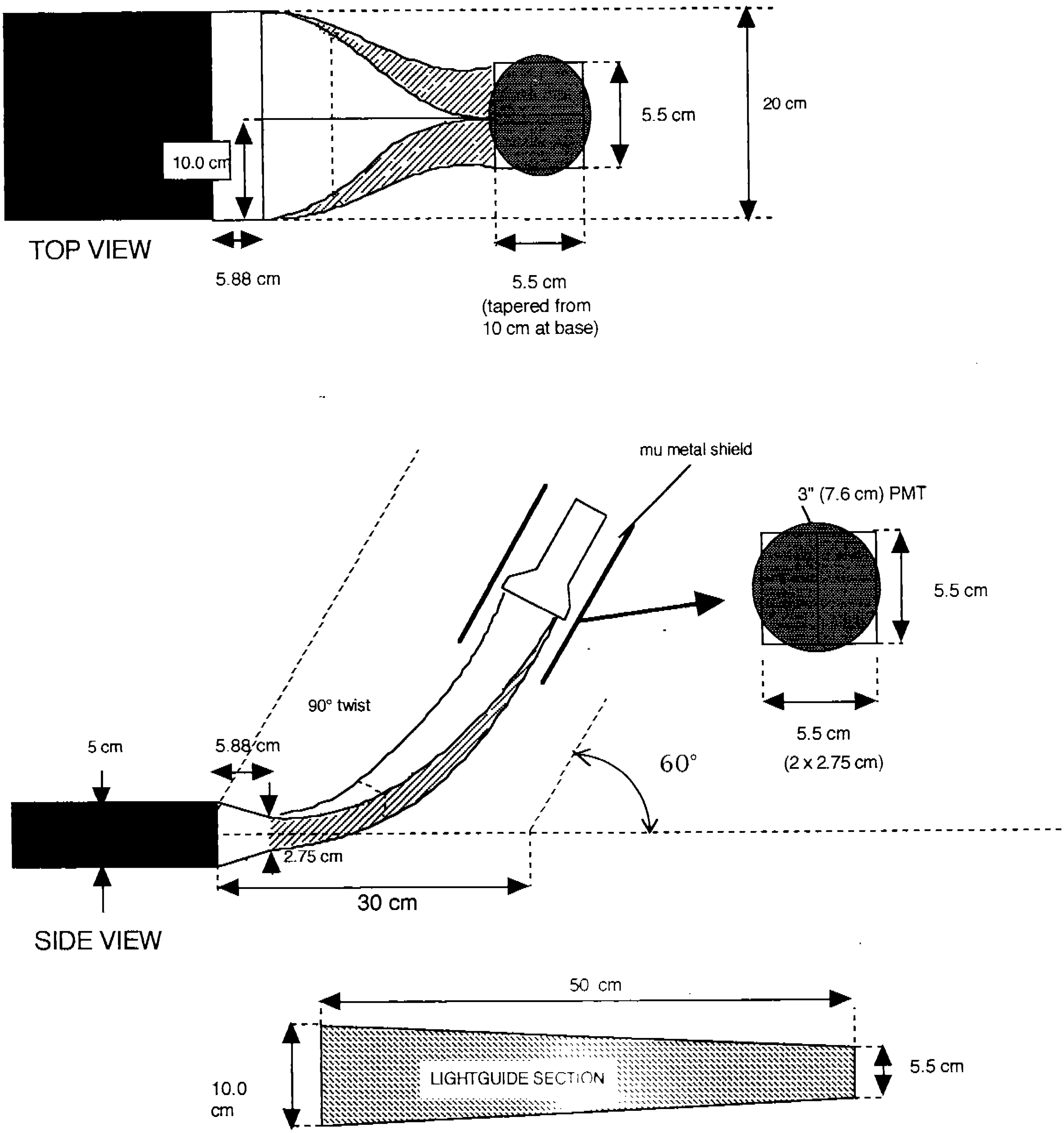


FIGURE 24