Light Guide Design for Phase 1 GlueX Sensor Module R & D Ver 1.3
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Abstract

The resulting light guide design to be used for Phase 1 of the Sensor Module R & D is shown together with the appropriate parameters from the results of Geant3 and WICO simulations and the required entrance and exit apertures.

1 Introduction

The GlueX Electromagnetic Barrel Calorimeter (BCAL) will consist of 48 modules such that each module subtends an angle of 7.5^o in the azimuthal direction. The BCAL has an inner radius of 65cm and an outer radius of 90cm, therefore having a thickness of 25cm and a trapezoidal shape with the inner face being 8.5cm wide and the outer face being 11.8cm wide. Constructing an array of lightguides to readout the BCAL poses a geometrical challenge in trying to match the geometry of the BCAL to devices for collecting the light for readout. To a first approximation we can make the entrance of the lightguides for readout square. Once a final readout design is chosen further studies can be carried out.

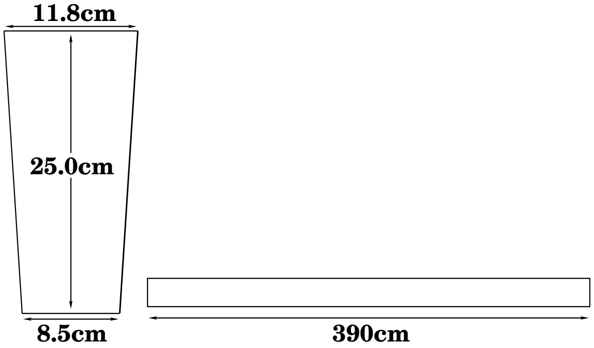

Figure 1: End-on view (left) and side view (right) of a single BCAL module

The precise shape of the required light guides is restricted due to the planned arrangement of such (or similar) light guides into an array. Ideal or nearly ideal nonimaging light concentrators, Compound Parabolic Concentrators (CPC), otherwise known as a Winston Cones, have circular entrance and exit apertures by symmetry of their design but they are not suitable for our design, due to their circular shape, which does not allow optimal segmentation for energy and momentum resolution. However, using the principles of CPCs we have designed a highly efficient light guide for our needs.

The designs of nearly all nonimaging concentrators are based on the edge-ray principle, namely that all rays at the extreme angle θ_{max} should leave the concentrator after one bounce. Rays that suffer more than one bounce generally tend to be reflected back and exit out the entrance. Rays with angles less then θ_{max} should then all exit the concentrator at the exit aperture. Cone shapes as well as paraboloids are good examples of simple designs of light concentrators, but are not ideal and have relatively low efficiencies compared to Winston cones. However, we will use this cone shape to taper our square entrance down to a round exit to which a Winston Cone will be attached. The light guide will be machined as one piece to reduce losses at the interfaces.

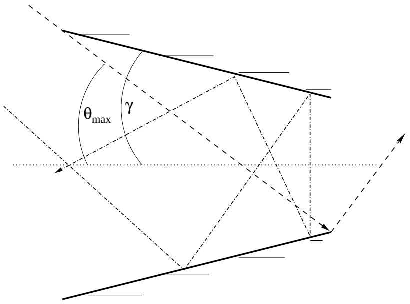

Figure 2: A cone shape will turn back some rays if the reflect more than once.

2 Light Guide Parameters

An index of refraction n=1.49 was assumed for the 10cm-long light guide. It consists of 3 segments: an untapered

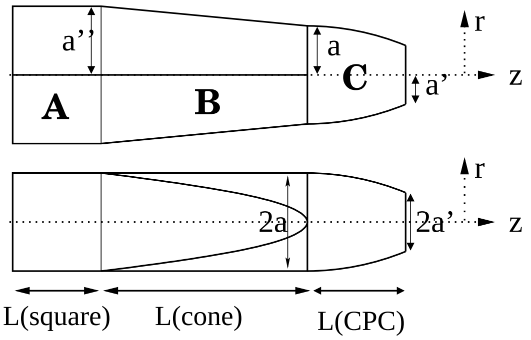

Figure 3: Top: 45 degree rotated view of lightguide. Bottom: side view.

rectangular block (segment A), a rectangular block tapered at the corners by a cone (segment B) and a Compound Parabolic Concentrator (CPC) otherwise known as a Winston Cone (segment C). The equations following will describe a surface that will most efficiently transport light from the 2x2cm^2 square entrance aperture to the 1.26cm^2 round exit aperture. The latter is the design requirement for large area SiPM-based Sensor Modules that are candidates for the BCAL readout devices due to their insensitivity to magnetic fields.

Segment A

$$\begin{aligned} Length \quad z_A &= 3.73697cm \\ Height \quad x_A &= 2.0cm \\ Width \quad y_A &= 2.0cm \end{aligned}$$

This segment (see Figure 3) is not entirely necessary but is included for ease of production and use. The length is chosen to make the overall length of the light guide an even 10cm. This extra length has almost no effect on the attenuation of the light as the attenuation length of the dielectric material is on the order of a few meters.

Segment B

This surface can be described as the previous 2x2cm^2 block but with the volume described by a cone being removed from the block so that the corners of the block are tapered down to a circular aperture. Equation 3 describes the inside surface of the cone. This is the new outside surface of the lightguide.

Monte Carlo

The included geometries within GEANT3[1] allowed us to simulate Čerenkov light in the green wavelength, within the tapered square-to-round portion of the light guide. First, the optimal tapering angle for this segment needed to be determined. This is mostly dependent on the maximum angle at which the light enters the light guide from the BCAL, which has an angle of 27.5 degrees for an index of refraction $n = 1.6$. This corresponds to the angle of total internal reflection at the interface between the first and second layer of cladding. In a medium with $n = 1.49$ this angle increases to approximately 29.5 degrees so our light guide should be designed with the latter θ_{max} in mind, and the simulations show that this is the angle we should choose for the tapered section. The length of the cone is calculated from

$$L = \frac{(a'' + a)}{tan\theta_{max}} \tag{1}$$

where $a' = \sqrt{2}cm$ and $a = 1cm$. The length of the light guide in the simulation is kept constant at 10cm such that the portion that is not tapered is still square and the changes in attenuation due to path length are minimized. We can see in Figure 4, that for a longer cone section with a shallower tapering, that the efficiency is fairly flat at $\eta = 0.96$ and drops off sharply at greater angles. In order to achieve maximum efficiency with minimal cone length and material costs (the length of the square section can be reduced) $\theta_{max} = 29.5^o$ is chosen for the tapered section of the light guide. Having this we can now describe the surface for Segment B.

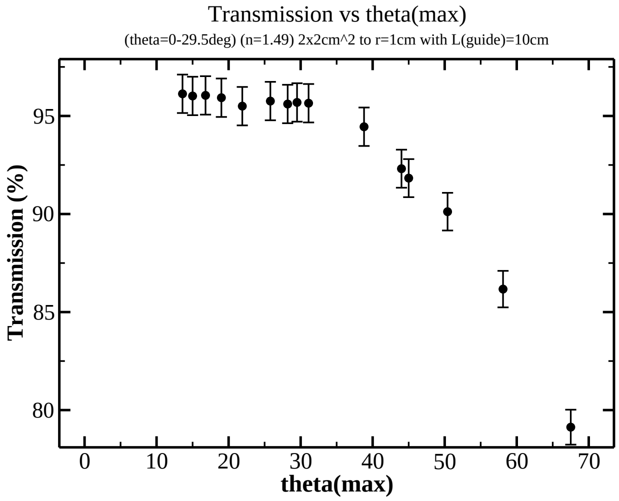

Figure 4: GEANT3 simulation with $2{\times}2cm^2$ entrance and 1cm radius exit with a flat entrance theta distribution of 0 - 29.5 degrees and random azimuthal angle.

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[1] http://cernlib.web.cern.ch/cernlib/

Parameters

The origin for the equation [2], $z_B = 0$, lies at z_A.

$$r_B(z_B) = a'' - z_1\frac{(a''-a)}{(a''+a)}tan(\theta_{max_1}) \qquad (2)$$

where

$$a'' = \sqrt{2}cm$$

$$a = 1cm$$

$$\theta_{max_1} = 29.5^o$$

and

$$0 \leq z \leq L_{cone}$$

where

$$L_{cone} = \frac{(a''+a)}{tan\theta_{max_1}} = 4.27cm.$$

Putting the values into [2] we get, in cm,

$$r_B(z_B) = \sqrt{2} - (0.097071)\cdot z_1 \qquad (3)$$

The azimuthal components of $r(z)$ are then simply $x(z,\phi)$ and $y(z,\phi)$ where $0 \leq \phi \leq 2\pi$. The transmission curve for this segment, Figure 5, shows the transmission efficiency of light for given entrance theta. Notice that some fraction of light is transmitted all the way up to 42.5^o.

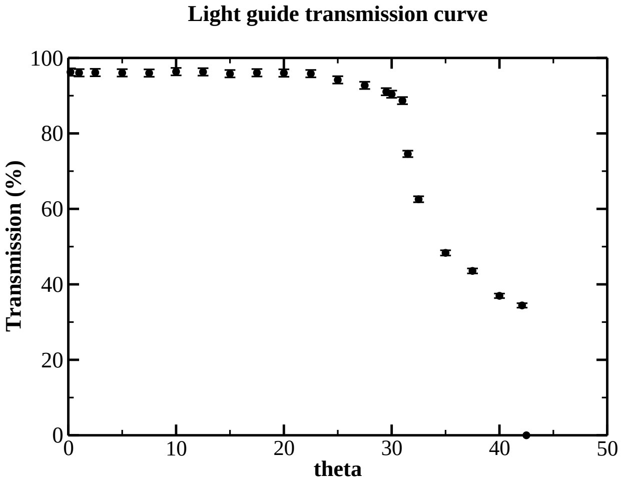

Figure 5: Transmission curve for discrete entrance theta and random azimuthal angles distributed randomly over the entrance aperture (no CPC attached yet).

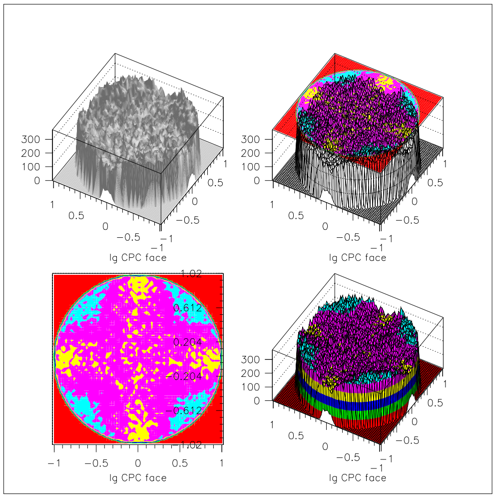

Figure 6: Surface plot of the 2-d histogram (x,y) of the exit aperture of the cone tapered section B.

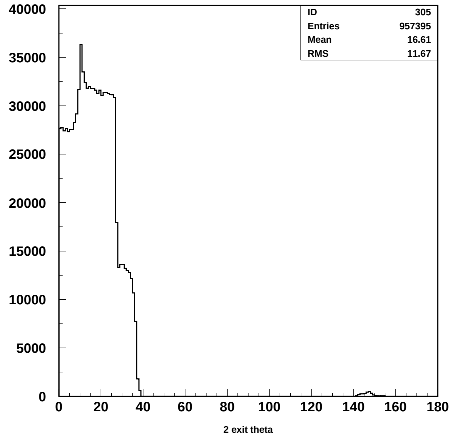

Figure 7: Exit theta of the cone tapered section B

Segment C

This is the Winston Cone section of the light guide. The properties of CPCs, or Winston Cones, are well known and have been shown to be nearly ideal due to their symmetrical properties [1]. Matching the entrance aperture of the CPC to the exit aperture of the tapered section and choosing the exit aperture of the CPC defines all the other parameters of the CPC. WICO[2], a simple ray tracing program, was used to calculate the efficiency of the CPC for various exit areas. Data from Figures 6 and 7 were used as input.

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[2] http://cernlib.web.cern.ch/cernlib/

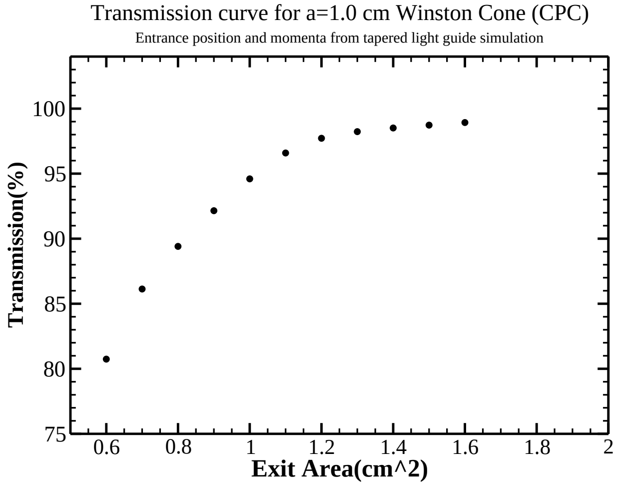

Figure 8: Transmission curve for CPC. Efficiency vs. exit area.

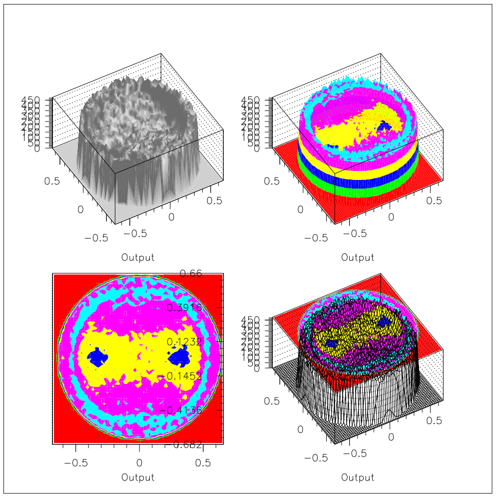

Figure 9: Surface plot of the 2-d histogram (x,y) of the exit aperture of the CPC of area $= 1.3cm^2$.

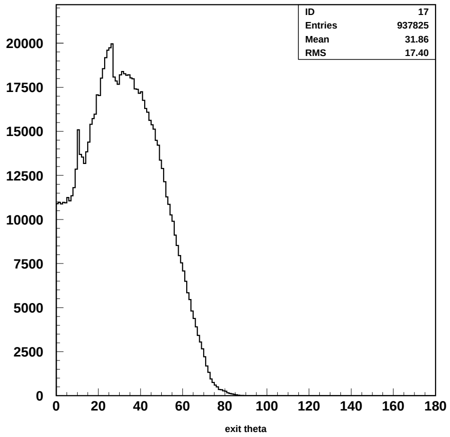

Figure 10: Exit theta of the CPC (area $= 1.3cm^2$). Notice the smearing to higher theta vs. Figure 7.

The exit aperture area, A, has been chosen to match the active area of the Sensor Modules. With

$$A = 1.26cm^2$$

we have

$$a' = \sqrt{\frac{A}{\pi}} = 0.633301cm$$

which gives us

$$\theta_{max_2} = sin^{-1}(\frac{a'}{a}) = 39.2941^o.$$

From [1] we get the equations describing the surface of the CPC. (The origin for the following, $z_C = 0$, lies at $z_A + L_{cone}$.)

$$r_C(\theta) = \frac{2a'(1 + sin\theta_{max_2})sin\theta}{1 - cos(\theta + \theta_{max_2})} - a' \tag{4}$$

$$z_C(\theta) = \frac{a'(1 + \frac{1}{sin\theta_{max_2}})}{tan\theta_{max_2}} - \frac{2a'(1 + sin\theta_{max_2})cos\theta}{1 - cos(\theta + \theta_{max_2})} \tag{5}$$

where

$$\theta_{max_2} \leq \theta \leq 90^o$$

This should give a length for the Winston Cone of

$$L_{CPC} \simeq 2.00cm.$$

and thus an overall length of 10cm.

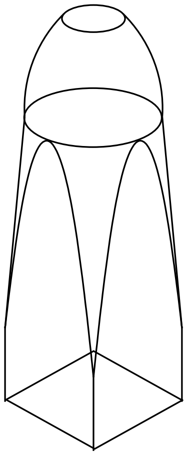

Figure 11: Top down view

3 Conclusions

By choosing the optimal parameters (for maximum efficiency) for Segment B from Figure 4 and Segment C from Figure 8 a lightguide with an overall efficiency of approximately $\eta = 0.90$ can be made. Equations [1-5] describe the surfaces and dimensions of a lightguide with this efficiency.

References

[1] W.T. Welford and R. Winston. *The Optics of Nonimaging Concentrators*. Academic Press, 1978.

Figure 12: A 3D rendering using Blender, an open source rendering program

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[2] www.blender.org