A Study of the Optical Properties of Prototype FCAL Light Guides

S. Adams, C. Cude, M. Shepherd, and B. Zihlmann
Indiana University, Bloomington, Indiana 47405

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Abstract

We present experimental results and Monte Carlo studies of the dependence of the transmission efficiency for cylindrical light guides for the FCAL as a function of light guide length and surface treatment. Light guides that are wrapped in aluminized mylar foil are more efficient than those that are unwrapped or have a vapor-deposited aluminum finish. Coupling of the light guides to the lead glass blocks can be achieved using a Sylgard cookie and the application of less than 2 pounds of force. Parallel alignment of the light guide and lead glass surface is critical. The final light guide and optical joint is expected to provide a net transmission efficiency for Cherenkov light that is 2.3 times larger than what can be obtained by coupling the phototube to the block with a small airgap, as used in the RadPhi experiment.

1 Introduction

A GEANT model of a single FCAL cell was developed in order to evaluate the ability of different light guide geometries to optimize the collection of Cerenkov light. These studies indicated that a simple right cylindrical acrylic light guide (i.e. a light pipe) with a reflective surface may be the most practical option to improve optical coupling and recess the PMTs into their magnetic shields. We have since attempted to verify accuracy of the simulation and confirm the effectiveness of the light pipes with a set of bench tests that can provide guidance on light guide development. In addition, methods for coupling the light pipes to the lead glass have been evaluated to find a viable technique for the full FCAL array.

2 Methods

Past measurements of optical efficiency have used an artificial light source to evaluate light guides without using cosmic rays. This involves routing light from a blue LED to mounting points attached to a lead glass block at 0°, 22.5°, and 45°. The light source and readout method are described in a previous note [1]. This method had the disadvantage that the PMT power supply had to be shut down during each change of the setup. To avoid this, the follow-up tests were carried out in a darkroom; in order to reliably align the block, light guide, and PMT in the dark we installed the PMT and lead glass in sliding mounts on a rail. Using this method, we were able to change light guides, establish a trustworthy grease joint, and take data with a very low level of light. The light source and readout were as in the previous tests [1]. As such, we are able to benchmark the simulation for the light source and configuration we use in the lab, but we can't directly check the simulation for Cherenkov light.

3 Validation of Simulation

The GEANT modeling studies suggest that it is not feasible to use a concentrating light guide to compensate for the geometric mismatch between the PMT active area and FCAL block size. Consequently, a reflective light pipe yielded the best photon collection efficiency under the constraints imposed by the need for magnetic

Table 1: The simulated performance of various light pipes. The data are given as a change in collection efficiency relative to the shortest light pipe in order to show the performance as a function of length.

	Bare			Foil wrapped		
Length	0°	22°	45°	0°	22°	45°
0.6 cm	-	-	-	-	-	-
1.25 cm	-2.4%	-4.7%	-6.0%	-3.6%	-4.4%	-2.6%
2.5 cm	-6.2%	-11.7%	-14.9%	-9.2%	-9.9%	-12.1%
3.2 cm	-7.8%	-14.0%	-17.0%	-11.5%	-10.9%	-12.1%
3.8 cm	-9.0%	-16.1%	-23.3%	-12.0%	-14.2%	-17.3%
7.6 cm	-16.1%	-27.1%	-40.3%	-19.5%	-25.0%	-33.3%

Table 2: The measured performance of various light pipes. The data are given as in the previous table.

	Bare			Foil wrapped		
Length	0°	22°	45°	0°	22°	45°
0.6 cm	-	-	-	-	-	-
1.25 cm	7.9%	-8.8%	-26.6%	-3.5%	-5.6%	-7.1%
2.5 cm	5.3%	-17.0%	-28.1%	-9.1%	-11.3%	-10.7%
3.2 cm	-4.8%	-25.2%	-32.8%	-12.6%	-12.9%	-16.1%
3.8 cm	-3.5%	-23.8%	-32.8%	-10.6%	-12.9%	-16.1%
7.6 cm	-7.0%	-26.5%	-42.2%	-18.2%	-23.4%	-32.1%

shielding and cost of materials. Such a light guide would ideally eliminate internal reflection in the lead glass and efficiently transmit photons to the PMT, thus emulating the behavior of a direct coupling with optical grease. The mirroring is necessary because the angular distribution of the Cherenkov light produced in the calorimeter cells and defocused by the step down in refractive index is such that total internal reflection is not sufficient to efficiently propagate most of the photons in the acrylic light pipe.

To validate these conclusions with a bench test, we used a model with geometry and light source specific to our test setup to generate a data set analogous to the measurements we can perform in the lab. The simulated data consists of collection efficiencies for light pipes ranging from 0.6 cm to 7.6 cm in length at mean photon incident angles of 0°, 22.5°, or 45°, and with or without an air coupled wrapping of 80% reflective aluminum. The results are presented in Table 1 below. The measured data are presented in Table 2. Note that for the light pipe without foil there is an enhancement due to leakage of light into the pipe from outside. This is not very relevant to the performance of the real detector for two reasons. First, the enhancement occurs primarily for photons at shallow angles, which are a relatively small portion of the Cherenkov angular distribution. Furthermore, these photons would be blocked by the μ-metal and soft iron tubes.

As expected, both data sets show that the efficiency of non-mirrored light pipes degrades more rapidly with increasing length. The collection efficiency of non-mirrored light guides does not decrease monotonically with length because photons may enter through its lateral surface, so the extent to which this occurs depends on the length of the light guide. This effect does not represent a practical efficiency gain since the magnetic shielding would block any photons that might be collected in this fashion. The most notable difference between the two data sets is that the real light pipes are less efficient than ideal simulated ones as the length increases. That this is true for mirrored and non-mirrored light pipes suggests, in addition to the fact that the foil is not 80% reflective, that the surface quality and transparency are over estimated. The optical properties of the light pipes were tuned in order to bring the simulation into agreement with the measured data. The result was a good match in the foil wrapped case, and close for bare light pipes of longer lengths. The short light pipes without foil still performed worse than the tuned model, perhaps because the surfaces

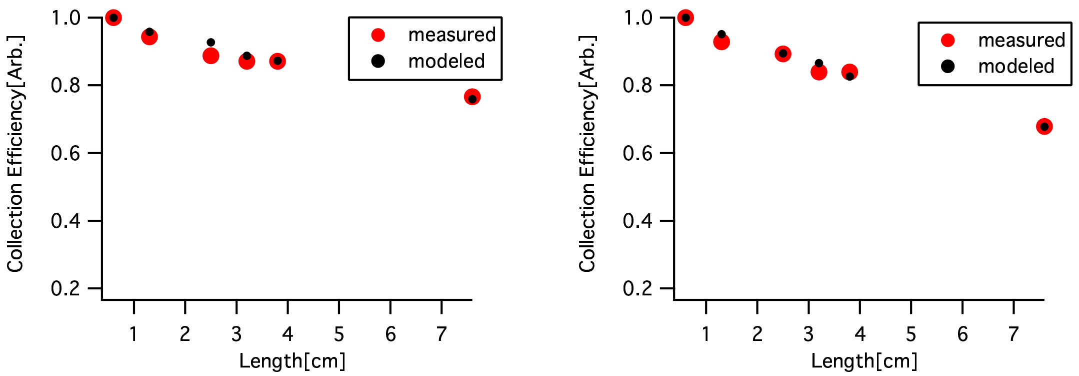

Figure 1: Normalized collection efficiencies for tested light pipes and the tuned simulation. The left (right) plot shows the comparison with the optical fiber mounted at 22.5°(45°).

Table 3: The optical properties of the light pipes were simulated using the UNIFIED model. The values in the table gave the closest match to the measured data for the foil wrapped light pipes.

Property	Value
Specular Spike Constant	0.9
Specular Lobe Constant	0.03
Diffuse Lobe Constant	0.07
σ_α	0.05
Absorption Length	70 cm
Foil Reflectivity	70%

are more difficult to keep clean without the protection of the foil. Note also that the values for the foil wrapped light guide at 22°and 45°are of the greatest interest, since these angles overlap with the bulk of the Cherenkov photons that will be generated in the detector (see Figure 1). The properties that yielded the best match are given in Table 3.

Further measurements compared a light pipe with a vapor deposited aluminum coating to uncoated light pipes with and without aluminized mylar wrapping. These results are given in Table 4. The light pipe with the vapor deposited coating does not benefit from the total internal reflection provided by the air gap associated with a foil wrapping, and in fact performs worse than a bare light pipe. Note also that for this light source the foil wrapped light pipe approaches the goal of preserving the performance of the grease joint, which suggests it should be able to do the same for the Cherenkov distribution. The values for the light pipe without foil in Table 4 have been corrected to remove the efficiency gains from the lateral surfaces of the light pipe that are not present in the real detector, as described above. In order to make this correction, we masked off the face of the light pipe in contact with the lead glass so that only photons entering through the sides of the pipe would be collected, and subtracted this from the unmasked value.

Table 4: The performance of various mirroring techniques relative to that of a direct optical grease coupling. The light pipe with the vapor deposited coating is 4.2 cm long, while the others are 3.8 cm.

	Foil	No foil	Vapor deposited
0°	-2.3%	-3.0%	-17.3%
22.5°	-10.1%	-26.5%	-62.0%
45°	-16.6%	-44.9%	-72.6%

4 Coupling technique

The lead glass bars and light pipes in the FCAL must be optically coupled. For individual, temporary joints, optical grease can be used, but in order to scale up to the full detector the couplings must be stable over long time periods, capable of being easily replaced channel by channel, and require a minimum amount of force to couple and remove. One available option to meet these criteria is a pad of silicon rubber, sold commercially as e.g. Sylgard (EJ-560). Pre-manufactured pads can be expensive, so the liquid components were purchased individually to determine whether these might be easily cast in the lab. However, the results were unsatisfactory, with attempts to cast single discs producing a significant meniscus or generally irregular surface. The hardness of the material varies, but it is in general stiff enough that noticeable imperfections are sufficient to complicate coupling. A viable middle ground between raw materials and pre-cut cookies was found in buying sheets of Sylgard and cutting it to shape with an arbor press and gasket cutter.

When clean, Sylgard pads are slightly tacky to facilitate optical coupling. While they remain well seated once in place, installation requires some force to squeeze out air pockets. One proposal to minimize this force was to develop a convex light guide tip that would provide a force gradient across the surface of the light pipe. Six variations of this type of light pipe were made on a CNC lathe, three having spherical tips with radii of curvature from 113 to 225 inches, and three having conical tips beveled at between 0.5 and 3.8 degrees. The shaped guides were more effective at coupling the center of cookies, but were incapable of coupling around the edges of the cookies without excessive force.

Testing revealed that, when properly aligned, a light guide could be optically coupled with the Sylgard pads with under 2 pounds of force. However, even a slight misalignment would cause the joint to require over 12 lbs of force in order to achieve complete optical coupling. The previous bench setup only allowed for one joint to be aligned at a time. Design and construction of a new setup using a 5×5 array has recently been finished that will allow for aligning multiple optical joints. This setup should help to confirm whether precisely aliging light guides for the experiment is feasible.

5 Conclusions

Comparing the performance of the tested prototype light pipes to those in the initial simulations showed that the assumptions for the reflectivity of the foil wrapping, surface quality of the light pipes, and possibly the transparency of the acrylic were overly optimistic. However, the overall behavior of the bench test is captured in the model once the light pipe surface properties are tuned. The simulated collection efficiencies for Cherenkov light reported in the previous study were based on the assumption of optically perfect surfaces in the light pipe and 95% reflective foil wrapping. Updating those simulations with the surface properties obtained here yields the lower set of points in Figure 2. This suggests a mirrored light pipe will perform well but that its length should be minimized. Furthermore, since vapor deposited aluminum seems to result in poor performance, there may be room for improvement in finding highly reflective foil and better surface preparation. Estimating the energy resolution of the calorimeter as in [1], a four centimeter light pipe gives a 20.8% collection efficiency leading to a estimated statistical term of $5.7\%/\sqrt{E(\mathrm{GeV})}$ in energy resolution. By comparison, the air gap configuration used in RadPhi gave a 9.0% collection efficiency leading to a statistical term of $7.3\%/\sqrt{E(\mathrm{GeV})}$. The GlueX light guide design is estimated to be 2.3 times more efficient than that used in RadPhi.

References

[1] C. Cude, R. Mitchell, M. Shepherd, and S. Teige, "An Optimization of GlueX FCAL Light Guide Design," *GlueX-doc 850.*

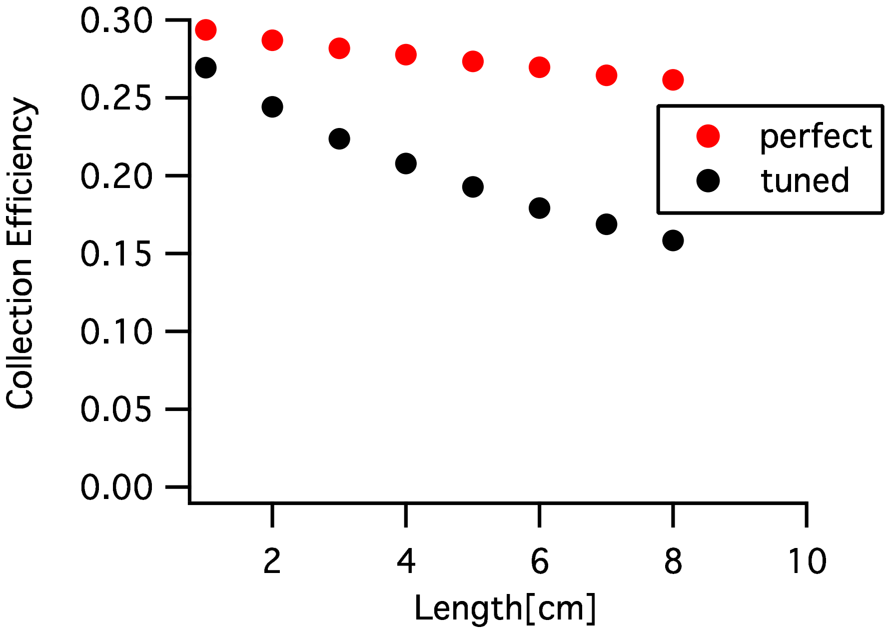

Figure 2: Comparison of the Cherenkov photon transmission efficiency of a light pipe with optically perfect surfaces and one with optical properties consistent with the measured data.