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Light transmission characteristics of scintillators for the pre-shower calorimeter

A. Daniel[1], J. Riso[2,3], S. Stepanyan[2], W. Tang[1], H. Voskanyan [4]

[1] *Ohio University, Athens, Ohio, USA*
[2] *Jefferson Lab, Newport News, VA, USA*
[3] *College of William and Mary, Williamsburg, VA, USA*
[4] *Yeravan Physics Institute, Yeravan, Armenia*

Abstract

The electromagnetic calorimeter for the CLAS12 detector will consist of the existing electromagnetic calorimeter as well as a new pre-shower calorimeter (PCAL). This note reports on the development of gluing procedure and the results of light transmission characteristics for the PCAL using the final scintillator bar design. Our studies shows that the scintillator bars with holes are challenging to glue partly because of the air pockets that develops during the curing process. However, we have developed a gluing procedure with good reproducibility. Also, our studies indicate that the use of two fibers per hole gives approximately the same transmission characteristics as a single fiber with glue.

1 Introduction

Calorimeters are mainly used to identify electrons, photons, $\pi^0 \to \gamma\gamma$, and neutrons. The forward region of the CEBAF Large Acceptance Spectrometer (CLAS) is equipped with a forward electromagnetic calorimeter [1]. This calorimeter consists of six identical modules, one for each sector of the six CLAS sectors.

The calorimeters for the CLAS12 detectors must have sufficient radiation length to absorb the full energy of the electromagnetic showers initiated by high energy electrons and photons. Also, a good part of the CLAS12 physics program requires the detection of neutral pions. In the current configuration, the EC will not be able to resolve a single high energy photon from the two photons that were produced from the π^0 decay. For example, the single high energy photon produced in the reaction $ep \rightarrow ep\gamma$ cannot be distinguished from the photons that are produced from decay of π^0 from the reaction $ep \rightarrow ep\pi^0$ due to close proximity of two photon clusters on the EC plane. To solve this problem, a finer granularity of the shower energy in the transverse plane is required [2]. The conclusion of the physics studies indicated that a Pre-shower Calorimeter (PCAL) must be placed in front of the Electromagnetic Calorimeter (EC).

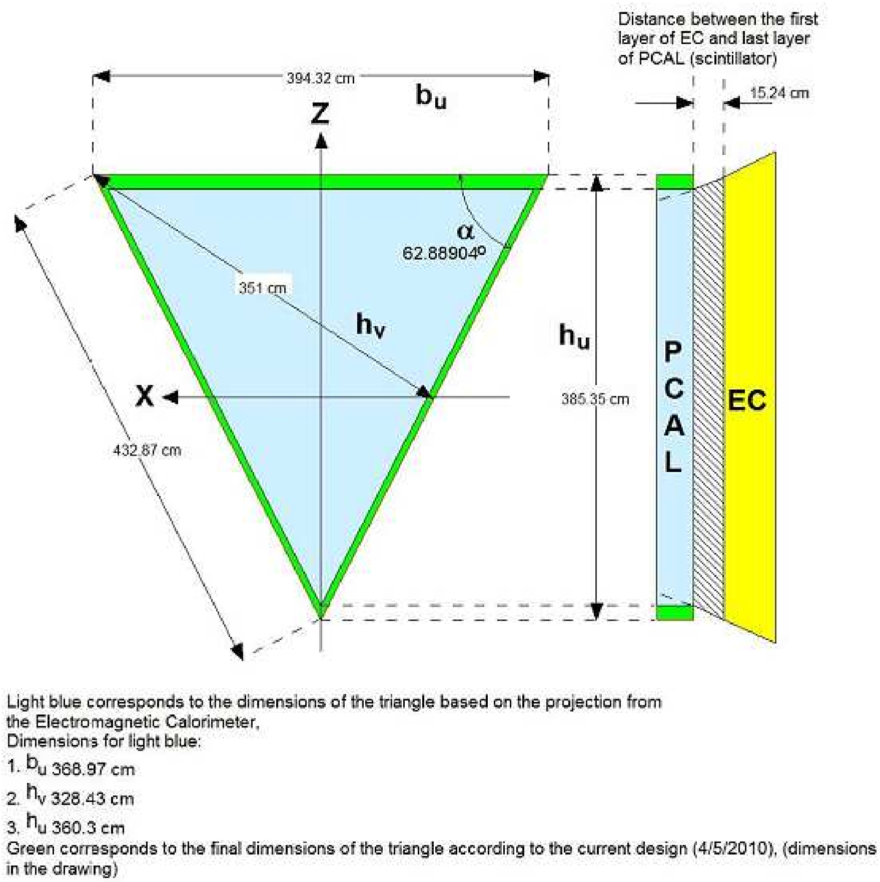

Figure 1: The figure discusses the dimensions and orientation of a sector of the PCAL. The existing electromagnetic calorimeter is shown in yellow color.

The PCAL will have a geometry similar to the EC and will be positioned in front of EC (see figure 1) to cover the full angular acceptance of the EC. The PCAL will be composed of six sectors or modules [3], each sector will consist of alternated layers of lead and scintillator, with three stereo readout planes named U, V and W. Each layer would consist of scintillator barss running parallel and arranged at ≈ 120 degree relative to the previous layer. Each sector will be composed of five U layers, five V layers and five W layers. The dimensions of the scintillator bars are shown in figure 2.

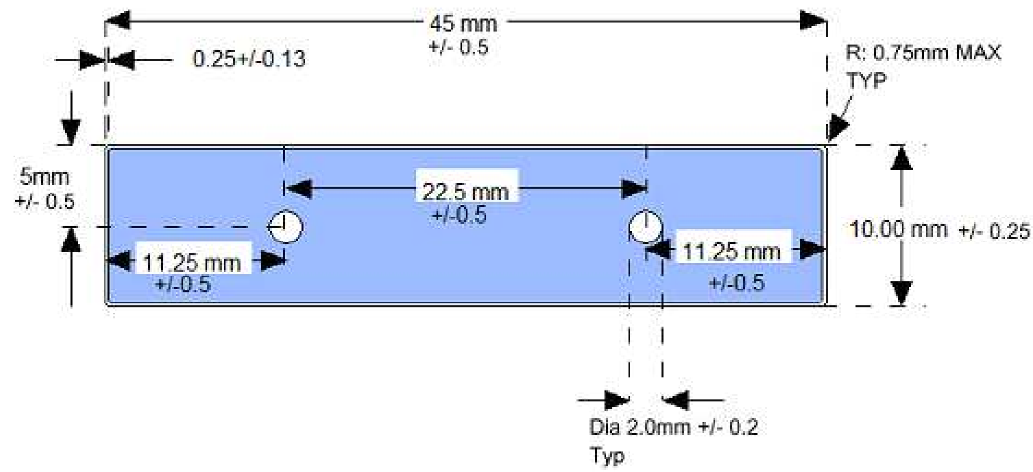

Figure 2: The figure shows the cross-sectional view and dimensions of a scintillator bar that will be used for the construction of the PCAL. According to FNAL, for an extrusion with this dimensions, the hole will be oval ranging in size 1.8 to 2mm by 2.5 to 2.8mm.

The shower of charged particles traversing the scintillator strips will produce tracks of blue light, the photons produced will be transported to the photomultiplier's photocathode via wave length shifting fibers (WLS) that runs through holes co-extruded in the scintillator. In the initial design, it was proposed to use epoxy to fill-up the space between the fiber and the inside surface of the hole to match the index of refraction of the fiber and scintillator, and, consequently increase the quantity of light transmitted in the interface. The question aroused as to how the holes can be efficiently be filled with epoxy for the large scintillator pieces avoiding air bubbles and pockets. Also it is important to characterize the light transmission characteristics of the scintillator with and without epoxy. This note addresses the gluing procedure developed for long scintillator pieces and discusses the results of different tests that were performed to characterize the light transmission properties.

2 Details of the measurements

2.1 Dimensional checks

In order to achieve a uniform response over the area covered by PCAL, the transmission properties of the scintillator bars needs to be characterized. The tests discussed in this note were performed in the EEL building of Jefferson lab and were done using scintillator bars provided by FNAL. These scintillator bars were produced as a result of the final test and tune of the JLAB's extrusion die on the FNAL-SDD extruder. The scintillator bars had a white diffuse reflecting surface composed of TiO_2 and polystyrene, this layer is co-extruded during the manufacturing process and has a thickness of 0.25mm. Each strip has two holes through the length of the bar, these holes were also co-extruded during the manufacturing process (see figure 2). Typically, the measurements were done on 10mm thick scintillator bars, 4.5cm wide and typical length was greater than 250cm (although we have measured several large and small pieces, results for smaller bars are discussed in [4]). Results of the dimensional check on several scintillator bars are shown in figure 3 and 4. Scintillators were selected randomly from the available supply for these studies.

In order to increase the accuracy of the measurement it was decided to measure the total width and thickness of several pieces of scintillator stacked. It consisted of stacking several scintillators and we measured the total width and height of the stack along the length of the scintillator. Figure 5 shows the result of these investigations. For the width measurement, 7 scintillator bars were arranged on a flat surface one next to each other in close contact and then measured the total width of the stack. For the thickness measurements, 15 scintillator bars were used, these were arranged on the top of each other. Measurements were done along the length in both sides of the scintillator bars (as denoted two different colors in the bottom plot of figure 5). The results of the dimensional measurements indicated that the tolerances are well within the design specifications of the scintillator bars.

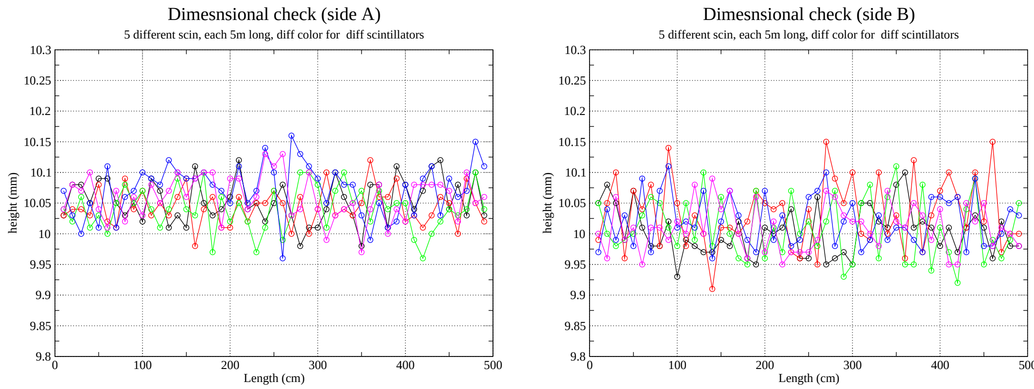

Figure 3: Shown are the result of thickness measurement along the length of the scintillator bar for the two different sides. Different colors represent different scintillator bars. The scintillator bars are provided by FNAL and the nominal thickness of a strip is 10 mm.

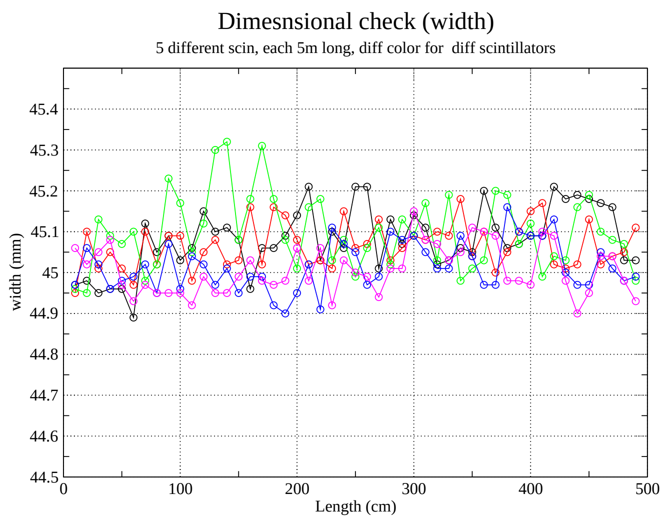

Figure 4: Shown are the result of the width measurement along the length of the scintillator taken alternatively from the two opposite sides. Different colors represent different scintillator bars. The scintillator bars are provided by FNAL and the nominal width of a bar is 45 mm.

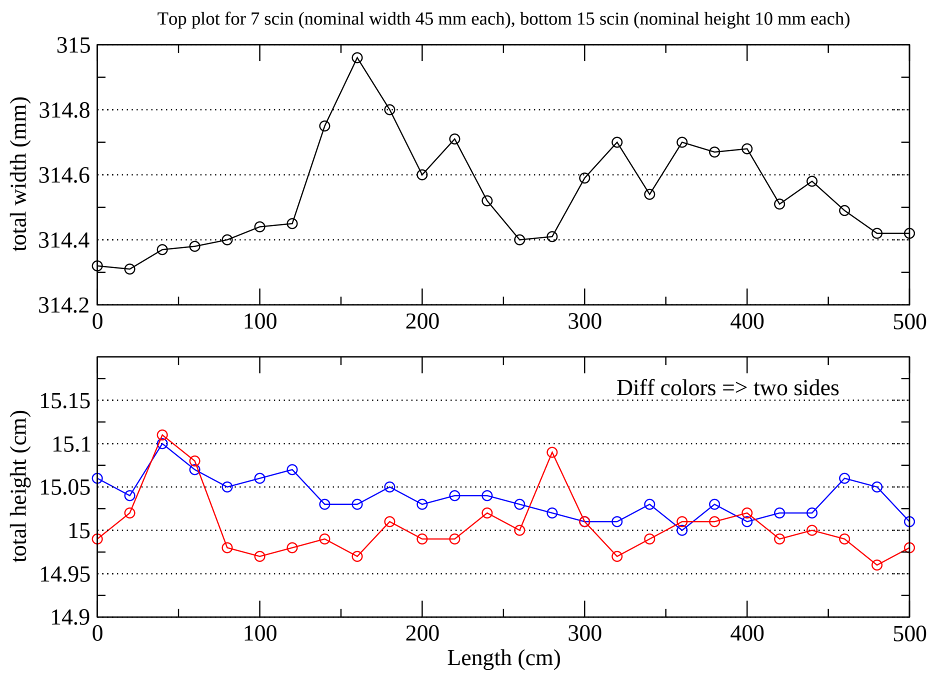

Figure 5: Shown are the results of the total width (top plot) and total height of the stack (bottom plot). Different colors in the bottom plot represents the thickness measurements done on the opposite sides of the scintillator bar. For the width measurement, we used a total of 7 scintillator bars and for the thickness measurements we used a total of 15. Nominal width of a bar is 45 mm and the nominal thickness is 10 mm.

2.2 Procedures

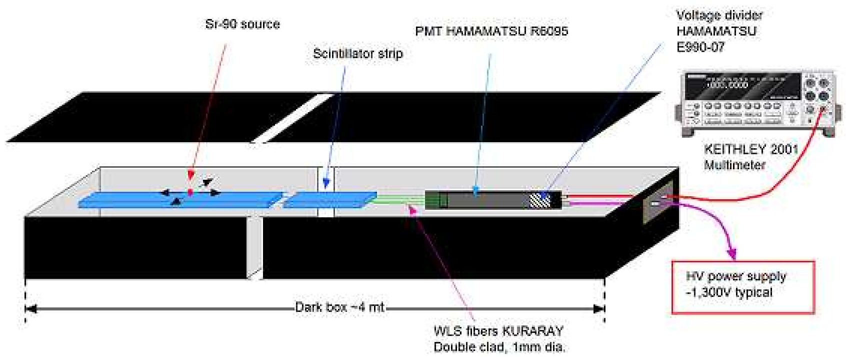

Figure 6: Shown is the setup inside the light tight box.

The scintillator strips were cut at an angle on both ends to match the edges of a sector's triangle. We used a ^{90}Sr (β) source for irradiation which moved along the length of the test piece. Attenuation length for extruded polystyrene scintillator for blue light (400–450 nm) bars ranges between 20–50 cm. This is far too small to adequately transmit light for the long bars. Due to the poor attenuation length of the extruded scintillators, the emitted scintillator light is collected locally by the wavelength shifting fibers (WLS). They are embedded in the bars (parallel to the length). The blue light is absorbed in the WLS fibers and re-emitted as green light that then travels down the fiber until reaching the PMT. Kuraray, Y-11 1mm s-type multi-clad fibers were used for the investigations mentioned in this note. The fiber was glued to the scintillator with BICRON BC-600 resin and hardener. The resin and hardener were mixed thoroughly in a plastic container. Immediately after mixing the epoxy was placed in a vacuum jar and exposed to a pressure of about 500 Torr for approximately 5 minutes to reduce the air content in the mix. If not carefully treated and injected, air bubbles accumulate to form air pockets along the scintillator holes. These local air pockets can cause uneven light transmission across the scintillator and can possibly influence the attenuation length.

The fibers from the scintillator bar were connected through a plastic adaptor to the photocathode of the PMT, the coupling made with optical grease. The fiber runs about 20 cm from the edge of the scintillator. The photomul-

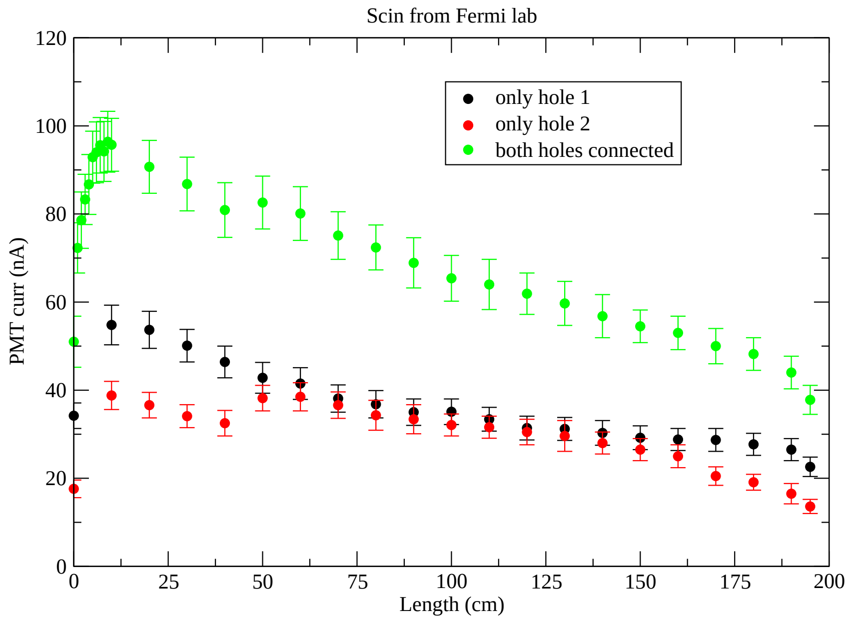

Figure 7: Shown is the dependence of the PMT anode current on the source position. The red and black color shows the individual response of the fibers from the holes while the green color shows the total response.

tiplier used was a Hamamatsu R6095 which was operated at 1300V. The full assembly was placed inside a light tight box. The placement of the source to the desired spot for the longitudinal measurements was controlled from outside the box by means of a string loop. This string, inside of the dark box was attached to a fixture which moved the ^{90}Sr source along the axis of the scintillator strip the see figure 6). For tests with epoxy, WLS fibers were inserted into the holes and then epoxy was injected to fill up the volume of the hole. The photomultiplier anode current was measured with a digital multimeter (Keithley 2001). This multimeter has storage capability which allows to analyze and display the average of several readings and the standard deviation associated with it. Typically we take the average of about 600 values for a single reading at a given position. The dark current was monitored and is subtracted from the measured signal for the data presented in this note.

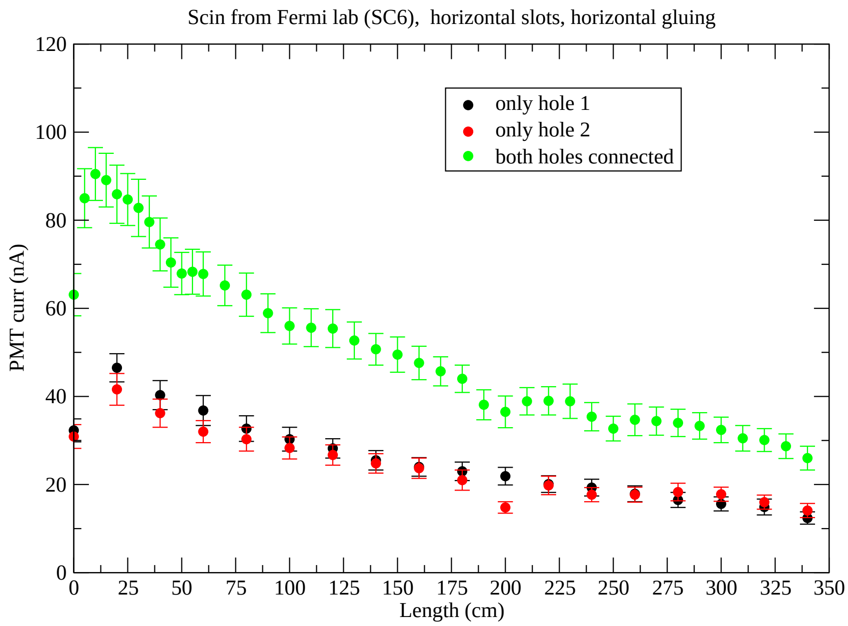

Figure 8: The figure shows the dependence of the PMT anode current on the source position. Gluing was done in a nearly horizontal postion. The red and black color shows the individual response of the fibers from the holes while the green color shows the total response.

A series of tests had been done in order to find the optimal gluing procedure. The scintillator bars were secured to a fixture (mounted 45 degrees from the horizontal) and the epoxy was injected slowly from the bottom of the bar using an epoxy dispenser. One problem that we encountered while gluing, is the shrinkage ($\approx 3\%$) of the glue, this shrinkage reduced the height of the column of epoxy by $\sim$15–20 cm during the initial hours of the curing period. This might cause an uneven response in the spectrum. An example is shown in figure 7. This figure shows the dependence of the PMT anode current versus the source position. For all the plots shown in the note, measurments starts from the end where the fiber from the scintillator bar is connected to PMT, and, the epoxy was injected from the opposite end. In the figure, the red and black color shows the individual response of the fibers from the holes while the green color shows the total response. These measurements were performed after gluing. Ideally the black and red points should show approximately the same behavior, however, there can be some differences between them. This could be due to problems with the fiber itself (micro cracks, damage to core/clad ...), or due to the problems in the fiber-PMT coupling. The latter could show up as a scale difference between the readings while the former can introduce a scale factor as well as position dependence. As one can see the near end and far end (of red points) have non uniform response of the light yield. This might be partially due to the shrink of the glue and also might be due to problems associated with the epoxy injection itself.

Several tests had been done to avoid the aforementioned problems, since for large scintillator strips the shrink of the glue can potentially affect the uniformity of the light response. Different steps were taken to alleviate this problem such as varying the angle between the scintillator bar and the horizontal plane while gluing, slow injection of the epoxy, several types of reservoirs at the far end, etc. Some of results of these studies will be discussed in the following paragraphs.

Figure 8 shows the PMT anode current vs. source position. This time the gluing was done in nearly horizontal position. To compensate for the effect of the shrink we used a reservoir at the opposite end of the injection side. The reservoir was a small slot (which was large enough to compensate for the amount of shrink) made at the far end of the scintillator piece. A piece of rubber was glued (using DP125) to the injection side. Gluing was done very slowly from this side and the reservoir was also filled with glue. However, this was not particularly successful as one can see from the figure. Still there is non-uniform response of the light yield. Another method was to use a rectangular slot (instead of horizontal slots). This is a rectangular slot of $\sim$35mm long, $\sim$7mm deep and $\sim$7mm wide. In this setup, gluing was done by keeping the scintillator bar in a vertical position. This method was not successful either, lack of uniformity was again observed in the light yield. Also, machining bigger slots in the scintillator is not a good idea since the slots will be in the active region of the detector and the light response from the edges could be problematic and this is exactly what we are trying to avoid by providing slots as reservoir for the glue.

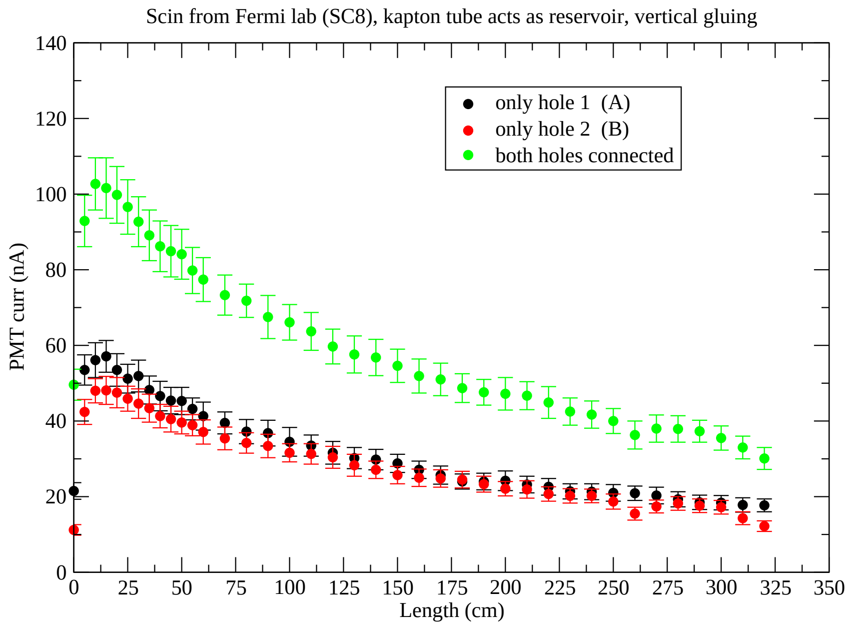

Figure 9: Shown is the dependence of the PMT anode current on the source position. Gluing was done with the scintillator bar nearly in horizontal position. The red and black color shows the individual response of the fibers from the holes while the green color shows the total response.

These investigations were repeated with several types of reservoirs such as plastic tubing, Kapton tube, etc. at the end of the scintillator. The Kapton tube have an ID of 4mm and are about 30 cm long. A small hole was drilled near the opposite side of the PMT end and Kapton tubes were inserted into this hole. Fibers were inserted into the hole before the insertion of the Kapton tube. Fibers were routed through outside the Kapton tube, and the Kapton tube was UV glued to the end of the scintillator bar. This tube now can act as reservoir. After the initial preparations, the scintillator was kept in a vertical position ($\sim$ 60 degree from horizontal) and glue was injected from the bottom of the bar. After several iterations of the above method we were able to successfully glue the scintillator and the light response was uniform within the uncertainties (see figure 9).

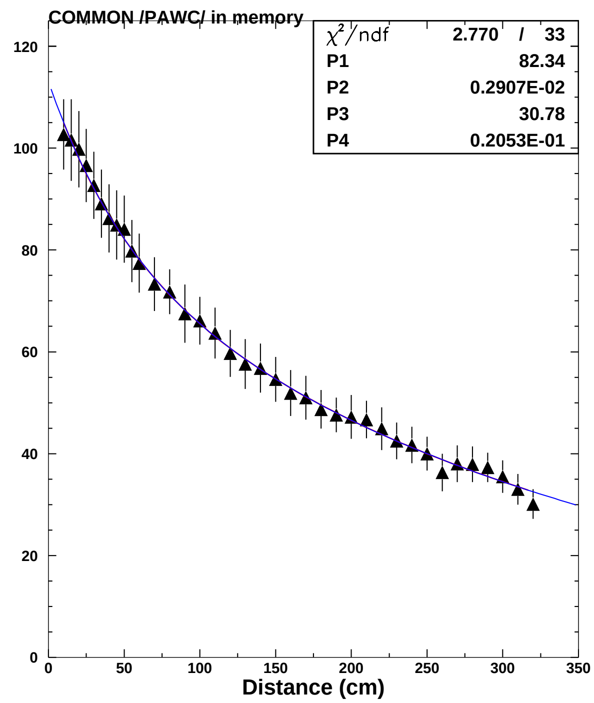

Figure 10: The figure shows the dependence of the PMT anode current on the source position. The response was fit to a double exponential as mentioned in text.

For monochromatic light (with no edge effects) the measured current should be $I \sim exp(\frac{-x}{\lambda})$ where λ is the attenuation length. However, in practice the response as a function of the position along the length of the bar can be fitted by the sum of two exponentials corresponding to a short and a long attenuation length.

$$f(x) = A\, e^{\frac{-x}{\lambda_{short}}} + B\, e^{\frac{-x}{\lambda_{long}}} \tag{1}$$

where λ_{short} and λ_{long} are attenuation lengths of the two spectral components and A and B are their corresponding intensities. A fit was done to the total current (green points in figure 9). The fit along with the parameters obtained for the previously mentioned figure is shown in figure 10. The parameters obtained from the measurements shown in figure 10 are λ_{short}= 49cm and λ_{long}= 344cm.

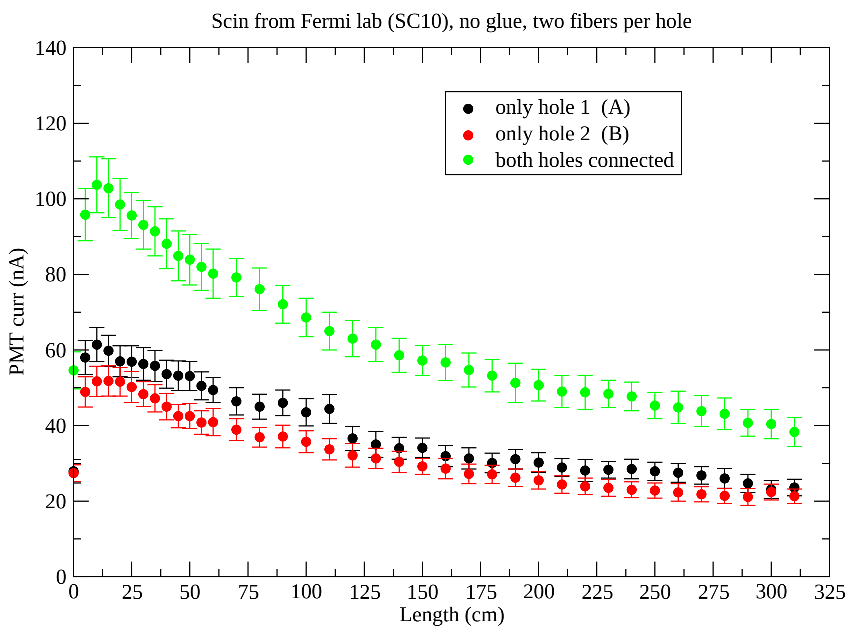

Figure 11: Shown is the dependence of the PMT anode current on the source position. This test was done without gluing the fiber inside the holes in the scintillator strip. There was 2 fibers per hole, so a total of 4 fibers per scintillator strip.

Due to the complexity of operations required by the use of epoxy, it was decided to study the response by not using epoxy. Two fibers were inserted in each of the holes of the scintillator bars. The fibers were routed through the holes leaving air to be the fiber-hole interface media, and, then the longitudinal measurements were repeated. Results of these tests are shown in figure 11. Note that for the tests conducted with gluing we used one fiber per hole. The behavior looks approximately the same as the strips with fibers glued in it. This is clearly visible in figure 12. From the figure one can conclude that the reduction in the light collection occurred by not using epoxy is approximately compensated by adding one more fiber in the same hole.

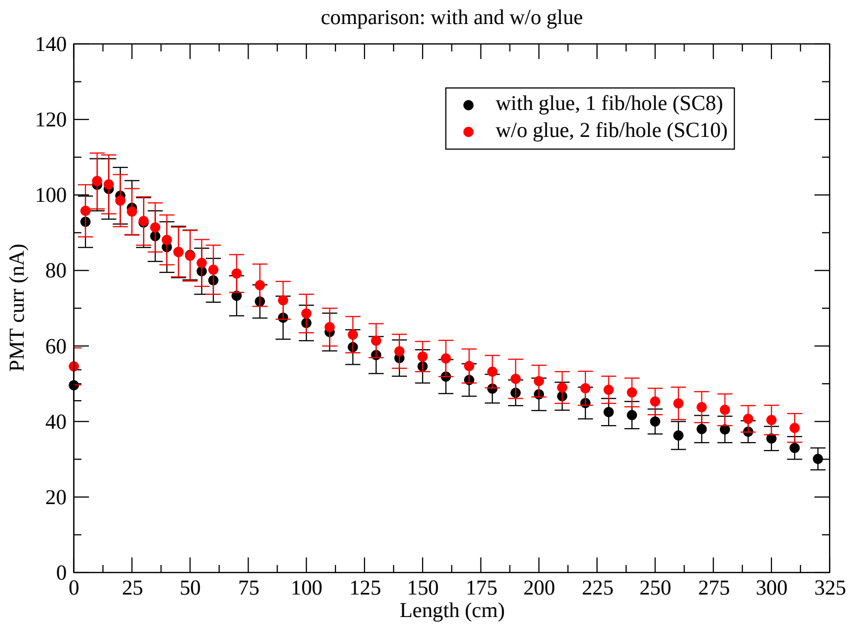

Figure 12: The figure shows the dependence of the PMT anode current on the source position. Red points represents the total average anode current without gluing while the black point represents the results with gluing. There was two fibers per hole for the strip without glue while there was only one fiber per hole for the strip with glue.

The entire test was repeated to check the reproducibility of the procedure and of the results. This time we used the same scintillator bars to measure the light yield. At first, the transmission characteristic was measured without gluing the fibers into the hole. After this measurement, we have repeated the gluing procedure as mentioned in preceding paragraphs. After curing we measured the light yield and the results are shown in figure 13. The main difference between figure 12 and figure 13 is that we used the same scintillator bar for the results shown for both measurements in figure 13. From these figures it is clear that with careful gluing, the results can be reproduced.

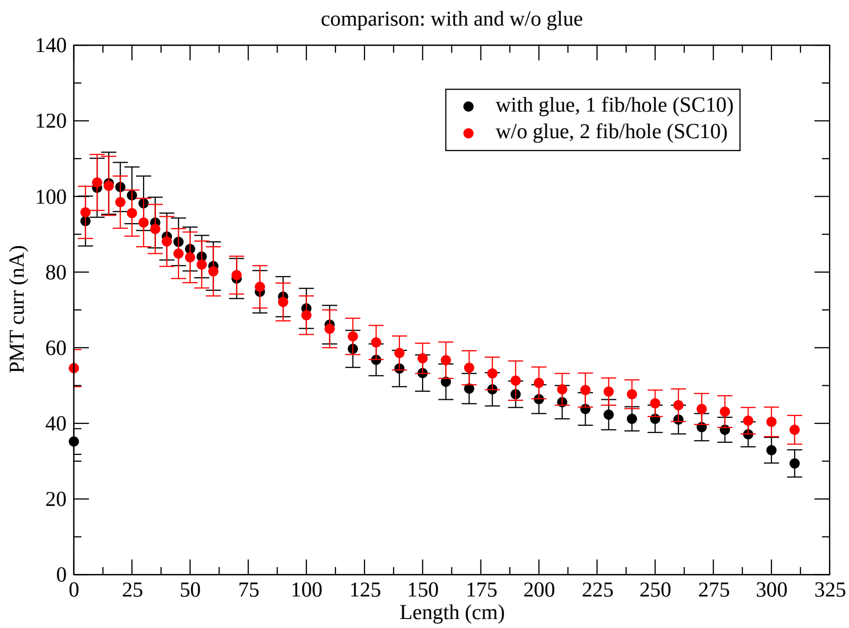

Figure 13: The figure shows the dependence of the PMT anode current on the source position. Red points represents the total average anode current without gluing while the black point represents the results with gluing. Shown are the results for same scintillator bar. There was two fibers per hole for the scintillator bar without glue while there was only one fiber per hole for the scintillator bar with glue.

With these series of studies it is evident that with careful treatment, to a large extent the air pockets can be avoided. However, the time needed for the gluing procedure takes up relatively large portion of the time when we compare the overall time devoted for the PCAL construction. Also, the process is labor intensive compared to the 'no glue' option. On the other hand, to compensate for the light loss that occurs without glue, one need to use an additional fiber in the same hole. In this case the cost of the extra fiber could be an issue. Also, the routing of fibers during the assembly will be better controlled without gluing them in the holes. For the tests we did, the fibers were just routed through the holes without securing them at the end. For the production we need to secure the fiber in position inside the hole using spot gluing at the ends of the bar.

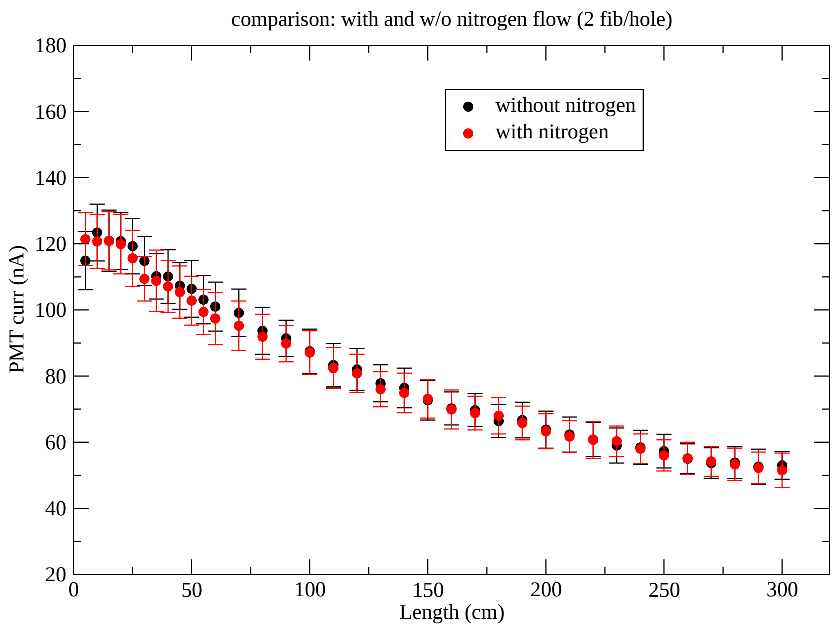

Figure 14: The figure shows the dependence of the PMT anode current on the source position. Red points represents the total average anode current without flushing nitrogen while the red point shows the results with nitrogen through the holes.

During operation, the volume of each PCAL sector will be purged using flow of nitrogen. Some tests were performed to investigate the effect of this on the light collection efficiency. The light tight box was modified for this purpose. Nitrogen was flush from the end of the box opposite to the PMT. Figure 14 shows the results of these studies. We used two fibers inside each hole and the tests were carried out with and without flushing nitrogen. From the figure it is clear that introduction of nitrogen atmosphere doesn't have any noticeable effect on the light transmission characteristics.

3 Summary and conclusions

To summarize, we have investigated several options for gluing fibers inside the holes of long scintillator bars for the use in the PCAL. The scintillator bars with holes are challenging to glue partly because of the air pockets that develops during the curing process. These air pockets cause non-uniform response. However, we have developed a gluing procedure with good reproducibility. This procedure needs careful attention and could be time consuming for large scale production. It was found that the use of an additional fiber in the hole gives approximately the same transmission characteristics as a single fiber with glue. We did some additional tests to gain some information regarding the use of nitrogen. It was found that the introduction of nitrogen atmosphere doesn't have any noticeable effect on the light output.

Additional tests needs to be done to characterize the absolute light yield of the scintillators. Also, the transmission characteristics needs to be further investigated by using a more intense radio-active source. The use of more intense source will give an opportunity to check the transverse response of the scintillator and the fiber system.

References

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