# Procedures of CLAS12 PCAL module construction

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# A. Introduction

To reconstruct the energy of high-energy showering particles and to separate high-energy $\pi^0$s and photons, a Pre-shower detector (PCAL) with finer granularity will be built and installed in front of the current EC. There will be six PCAL modules, one for each CLAS12 sector, see Figure 1. The PCAL module has a similar geometry as the current EC. Each module is a lead-scintillator sandwich with three stereo readout planes (U, V, and W). There are 15 layers of 1-cm thick scintillator layers, segmented into 4.5-cm wide strips, and sandwiched between 2.2-mm thick lead sheets. Lead and scintillator layers are confined between two endplates, Figure 2. The total thickness of the PCAL is about 5.5 radiation lengths. A variable width of the readout segmentation will be used to minimize the number of readout channels, without diminishing resolution in separation of close clusters. For the first 52 shortest strips in U and for the last 46 longest strips in the V and W stereo readout planes the 45 mm (single strip) segmentation will be used. For the remaining strips, 90-mm wide (double strip) segmentation will be used.

Thi**s** document discusses the procedures for cutting the scintillator strips, procedures for QA tests of scintillator fiber assembly, and for the stacking of scintillator-lead layers of the Preshower calorimeter, as well as the procedures for routing of Wavelength-shifting (WLS) fibers through the scintillator strips.

A partial version of a full-scale prototype was built in the EEL room 125 to get some insight into the optimal routing of the fibers and explore the different options for assembly of the PCAL modules, see Figure 3. These studies were aimed to obtain some information on the challenges one may face during actual construction of the PCAL. These include placement of photomultiplier tubes, methods for supporting and stacking the elements during the construction, methods of WLS fiber handling and routing of the fibers through the scintillator strips, methods for spot gluing, etc. One of the main goals behind the prototyping was to get some experience with the fiber routing. Bending of a fiber may cause some degradation of optical properties such as transparency, core/cladding composition of the fiber, and, hence can affect the light output. Thus, it is crucial to have some understanding of the bending and routing of the fibers.

The prototype discussed in this document is built in such a way that it mimics the PCAL dimensions at the three corners of the triangle. The actual size of the prototype differs from the nominal dimensions of the PCAL, however, for our investigations it is sufficient to reproduce the geometry of each corner. This is partly because the bending radius of the fibers are relatively small at the corners, and, thus investigating the fiber routing options in these region gives insight into the overall handling of the fibers for the large module. The bend radii of the WLS fibers are controlled by slots on the wall, which guide fibers into required path and eventually into the assigned PMTs. Rest of the document, provides an overview of the assembly of scintillator strips to form a module. Some of this information is derived from the assembly of the mini prototype. We will discuss the assembly of a single module; however, the procedure is the same for the assembly of all six modules of the PCAL.

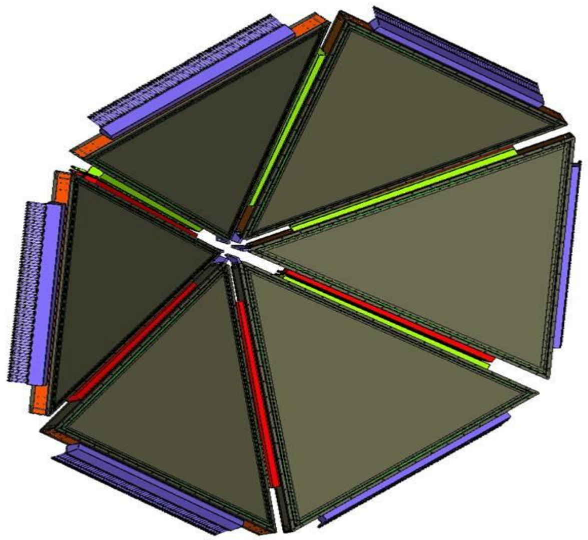

**Figure 1: Schematic diagram of the preshower calorimeter for the CLAS12 detector. The figure shows the six modules and the associated readouts for different views.**

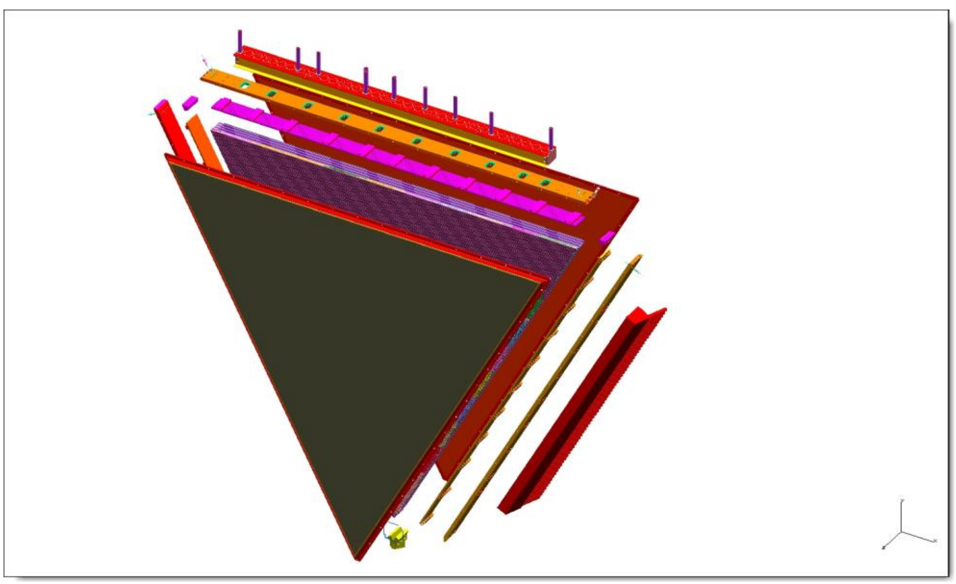

**Figure 2: Shown is the three dimensional CAD model of the box which contains the scintillator bars and lead layers for a module.**

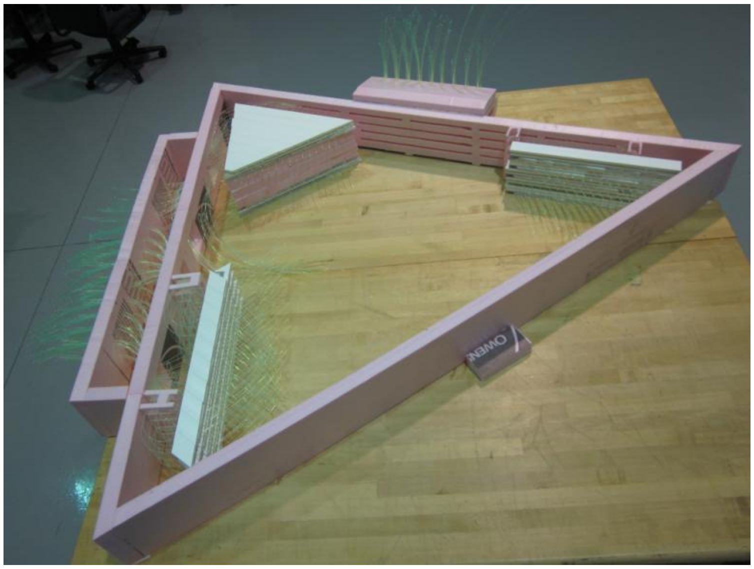

**Figure 3: Picture of the mini version of the PCAL prototype. Figure shows the different arrangement of scintillator layers and routing of WLS fibers from these layers to the wall**

## B. PCAL Basics

1) Scintillators of varying lengths but fixed cross section of 4.5 cm x 1 cm is combined into a layer of the PCAL. This layer forms a triangular geometry. Longest scintillator will form the base of the triangle and the shortest scintillator is located at the apex of the layer.
2) From beam direction, the first layer in the module is U view where scintillator strips are parallel to the side that is perpendicular to the beam direction. Strip lengths increase along the polar angle $\theta$ with respect to the beam direction. The next layer, V view, is rotated clockwise so that the scintillators are parallel to the next side of the triangle. In a similar manner the third plane, W view, has scintillators aligned with the third side of the triangle and is the mirror image of the V view, see Figure 4.
3) Lead sheets (2.2 mm thick), which acts as a radiator, are placed in between scintillator layers; and these sheets have the same dimensions as the scintillator layer (except for the thickness) and fully cover the scintillator layer.
4) This arrangement (U L V L W L) repeats 5 times, however, there is no lead layer (L) after the last scintillator layer. There are 5U, 5V, 5W and 14 lead layers for a module (sector).
5) When facing the beam, the PMTs on the left wall of the box (total number 68) will collect light from the U view. U layers consist of 84 strips each of nominal width 4.5cm and thickness 10 mm. For the U layer, the first 52 short strips at the apex of the triangle are read out individually. This means the first 52 strips on all

U layers are read out by a single PMT. For a single strip there are 4 fibers and for 5 layers of the given view we have 20 fibers read out by a single PMT in this arrangement. For the rest of the strips (32 long strips towards the base of the triangle) combination of two scintillator strips represent one readout channel. This means that two adjacent strips in all 5 layers are read out via single PMT. Thus at large angles 16 PMTs are used to read out all of the last 32 strips in the 5 U layers. In summary there are 16+52=68 PMTs on the left wall of each sector which will collect light from the U layers.

6) When facing beam, the PMTs on the top wall of the box will collect light from V and W layers. There are 78 strips for each V and W layers. Since there are 5 layers for each view, the total number of scintillator strips is 5 times 78 (for each view).
7) For V and W, longest 46 strips are read out individually using single PMT. For the rest of 32 shorter strips, combinations of two scintillators represent one readout channel. The total number of PMTs for V layer is 46 + (32/2) = 62 PMT. Similarly, W view also needs 62 PMTs. Thus in the top wall we have 62+62=124 PMTs, and for one module we have a total of 124+68=192PMTs.

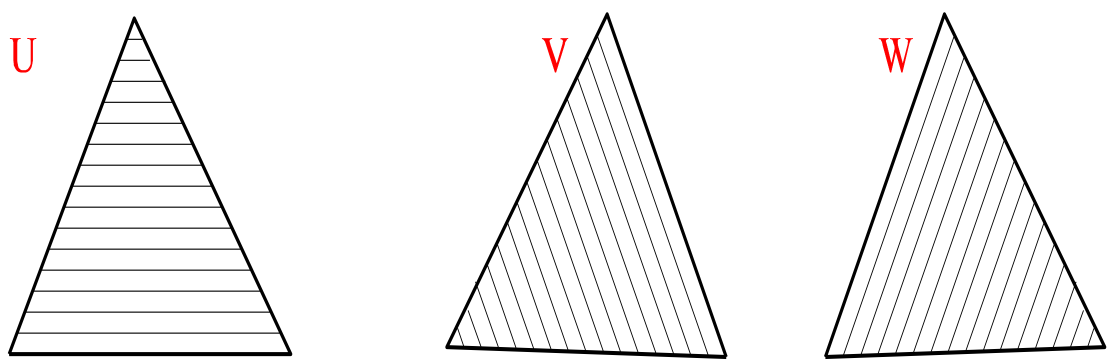


**Figure 4: Figure shows the schematics of the arrangement of the scintillator bars to form different views as mentioned in the text.**

## C. Procedures for assembly of PCAL box, for stacking of scintillator-lead layers, and for routing of WLS fibers

## Stacking of scintillator strips

a) All the parts of the PCAL box assembly must be cleaned from debris and grease left from the machining, use alcohol (isopropanol), work must be done in a clean, dust free environment, and workers must have gloves and clean-room coats.
b) Put the bottom window on a support table (3 sawhorses) and assemble side plates. Clean inside of the assembly and then install retainers. All of this must be done in accordance to the assembly drawings.
c) Lay down one layer of 0.05 mm thick Teflon sheets on the window to cover the area where scintillators will be laid.
d) First layer to be assembled is the U layer, then V and then W (see explanations above). Begin with the longest scintillator strip in a layer. Visually inspect the scintillator strips to make sure that the scintillator bars are in good condition. Clean strips from dust if necessary.
e) When stacking scintillator strips make sure that there is no space between the strips. Gaps between individual strips should be kept as small as possible, use shims (thin aluminum plates) at corner, where the smallest strip is, to push strips against each other. Make sure that each strip is tightly bound between retainer (at the fiber readout end) and the springs at the opposite end. If the strip is loose, put shims to compress about 1/3 of the strip.
f) After arranging the strips and finishing the layer, start inserting WLS fibers through the holes in the scintillator strip according to Table 1 (Table 1 contains information on optimal distribution of fibers for each layer and the length of scintillator bars for each view).
g) Visually inspect the WLS fibers to make sure that the fiber is in good condition.
h) For each hole, insert two fibers (note that there are 2 fibers per hole and hence there are 4 fibers per scintillator strip).
i) Begin inserting the fibers from the outside of the wall through the holes in the scintillator strip; fibers go through the hole in the sidewall that is near to the scintillator strip that is being worked on.
j) One person will carry the fiber bundle and another person will do the routing.
k) Once the fibers reach to the opposite end, cut the fibers according to the dimensions in Table 1. Dimensions are such that the fiber end should come out from the fiber holder holes at the PMT side by about 3 cm. Repeat this process for the second hole of the strip being worked on.
l) Once this is finished the four fibers are routed to the assigned holes of the base of the PMT housing according to Table 2 (Table 2 contains relation between strip number and the PMT).
m) By comparing with Table 1 decide whether the remaining pieces of fibers from above process is long enough for another strip in the same layer. If they are of sufficient length, repeat the routing procedure for that strip. If it is not sufficient

then discard the fiber, and start working on the next strip with a new bunch of fibers.

n) After finishing the routing of fibers for all strips in the layer, start testing each fiber for continuity and the correctness of the placement of the fiber to corresponding PMT base (please refer to Table 2). This test will be done by placing a light source (blue LED) on far end of a strip and photometer to the PMT base.
o) After satisfactory completion of above steps, spot glue fibers in to the scintillator strip. This procedure is discussed in next section.

## Spot gluing procedure

a) Gluing should be done at the far end to the PMT side.
b) Start the procedure from the longest scintillator bar. This procedure can be done on several strips (for example five) at a time.
c) Pull fibers out by about 1 to 2 mm from the hole. This is to make sure that we are spot gluing both fibers in the hole.
d) Glue the fibers to the scintillator. Make sure that the minimum amount of glue is used for spot gluing; we don't want to close the hole since we need to flush nitrogen through the holes. In order to control the amount of glue use a glue dispenser. Spot gluing tests were done with DYMAX optical UV curing adhesive OP-4-20632.
e) After putting the glue, insert a Teflon wire (< 2mm OD) into the hole from the upper side of the hole. This is to make sure that we have some space remaining for the airflow even after UV curing. Insert about 2 cm of the Teflon wire into the hole; we don't want to push the glue farther inside the hole.
f) After putting the Teflon wire, use UV light to cure the glue. For the tests, we used OminiCure spot curing system that was available in PCAL room. After about 15 seconds, carefully withdraw the Teflon wire from the hole, but continue curing for about 45 seconds more.

*Note: every one involved in this process must use protective glasses. Also, screens must be placed to avoid exposing others from the UV light.*

g) Once the spot gluing is done, put scintillators back in correct position.
h) Once gluing is completed for one layer, position scintillator strips using shims and springs. Make sure scintillators are secured properly and are tightly confined (see section C).
i) Cover scintillator layer with Teflon sheets.

## Stacking lead sheets

a) Lead sheets are ordered flat, precut in ½ layer size (right angle triangles). They must be clear from debris and must be deburred (manufacturer).

b) Use alcohol (isopropanol), to clean surfaces from any residual oil or dust, if flatness is not acceptable put the sheet on a wooden table and flatten it with wood blocks.
c) Using gantry crane and suction cups pick up a lead sheet and put on top of the scintillator layer. Make sure that the edge of the scintillators matches with the edge of the lead plate. Repeat this for the second half of the triangle.

*Note: This procedure must be done by trained personal.*

d) Shim lead sheets if needed.

After the satisfactory completion of the arrangement of scintillator strips, routing of fibers and placement of lead, start working on the next layer by following previous steps. Cover the lead layer with Teflon sheets before stacking the next layer of scintillators.

Remember that after the $15^{th}$ scintillator layer, there are no lead sheets. When finish stacking of the $15^{th}$ layer of scintillators (W-view) and routing and spot gluing of fibers, cover it with Teflon sheets and put the top window of the module and bolt it down to side walls. Follow the procedures on the engineering drawings.

## D. Procedures for gluing of fibers to PMT housing base

At this point, we already have done the necessary tests to make sure that the fibers are routed to the correct PMT housing bases and are ready to be glued at the PMT base. This gluing is to fix fibers in place for polishing and for connecting to the PMT cathode.

a) Fibers are glued into the PMT housing base with DB-190 glue.
b) Fill up the holes on the housing with glue using a syringe. Make sure to move/shake fibers so that glue will reach the bottom of the housing base.
c) After the gluing, fibers end will stay out of the base surface by a few centimeters. Later these protruding fibers will be cut and polished.

| Strip | Length (mm) | WSF length ( mm) | Strip | Length (mm) | WSF length (mm) |
|---|---|---|---|---|---|
| U1 | 120.1166 | 970.1166 | U43 | 2054.657 | 2606.657 |
| U2 | 166.1922 | 1009.192 | U44 | 2100.732 | 2645.732 |
| U3 | 212.2678 | 1048.268 | U45 | 2146.757 | 2684.757 |
| U4 | 258.318 | 1087.318 | U46 | 2192.833 | 2723.833 |
| U5 | 304.3936 | 1126.394 | U47 | 2238.908 | 2762.908 |
| U6 | 350.4692 | 1165.469 | U48 | 2285.035 | 2802.035 |
| U7 | 396.4686 | 1204.469 | U49 | 2331.06 | 2841.06 |
| U8 | 442.5188 | 1243.519 | U50 | 2377.135 | 2879.135 |
| U9 | 488.5944 | 1282.594 | U51 | 2423.211 | 2918.211 |
| U10 | 534.6192 | 1320.619 | U52 | 2469.286 | 2957.286 |
| U11 | 580.7202 | 1359.72 | U53 | 2515.337 | 3001.337 |
| U12 | 626.7958 | 1398.796 | U54 | 2561.387 | 3035.387 |
| U13 | 672.846 | 1437.846 | U55 | 2607.462 | 3079.462 |
| U14 | 718.9216 | 1476.922 | U56 | 2653.538 | 3113.538 |
| U15 | 764.9718 | 1515.972 | U57 | 2699.563 | 3157.563 |
| U16 | 811.0474 | 1555.047 | U58 | 2745.638 | 3191.638 |
| U17 | 857.0976 | 1594.098 | U59 | 2791.714 | 3235.714 |
| U18 | 903.1224 | 1633.122 | U60 | 2837.739 | 3269.739 |
| U19 | 949.198 | 1672.198 | U61 | 2883.814 | 3313.814 |
| U20 | 995.2736 | 1710.274 | U62 | 2929.839 | 3354.839 |
| U21 | 1041.349 | 1749.349 | U63 | 2975.966 | 3395.966 |
| U22 | 1087.425 | 1788.425 | U64 | 3021.99 | 3441.99 |

| | | | | | |
|---|---|---|---|---|---|
| U23 | 1133.45 | 1827.45 | U65 | 3068.066 | 3500.066 |
| U24 | 1179.525 | 1866.525 | U66 | 3114.065 | 3567.065 |
| U25 | 1225.601 | 1905.601 | U67 | 3160.141 | 3625.141 |
| U26 | 1271.651 | 1944.651 | U68 | 3206.191 | 3692.191 |
| U27 | 1317.701 | 1983.701 | U69 | 3252.267 | 3750.267 |
| U28 | 1363.777 | 2022.777 | U70 | 3298.368 | 3817.368 |
| U29 | 1409.852 | 2061.852 | U71 | 3344.443 | 3875.443 |
| U30 | 1455.903 | 2099.903 | U72 | 3390.494 | 3942.494 |
| U31 | 1501.953 | 2138.953 | U73 | 3436.544 | 4000.544 |
| U32 | 1548.028 | 2178.028 | U74 | 3482.619 | 4067.619 |
| U33 | 1594.104 | 2217.104 | U75 | 3528.695 | 4125.695 |
| U34 | 1640.129 | 2256.129 | U76 | 3574.745 | 4192.745 |
| U35 | 1686.204 | 2295.204 | U77 | 3620.821 | 4250.821 |
| U36 | 1732.28 | 2334.28 | U78 | 3666.896 | 4317.896 |
| U37 | 1778.305 | 2373.305 | U79 | 3712.921 | 4375.921 |
| U38 | 1824.38 | 2412.38 | U80 | 3758.997 | 4442.997 |
| U39 | 1870.456 | 2451.456 | U81 | 3804.971 | 4500.971 |
| U40 | 1916.532 | 2489.532 | U82 | 3851.046 | 4568.046 |
| U41 | 1962.556 | 2528.556 | U83 | 3897.173 | 4526.173 |
| U42 | 2008.632 | 2567.632 | U84 | 3943.248 | 4693.248 |

**Table 1a:** Table shows the length of scintillator bars and the optimal length of fibers for the V layer.

| Strip | Length (mm) | WSF length (mm) | Strip | Length (mm) | WSF length (mm) |
|---|---|---|---|---|---|
| V1 | 55.6768 | 585.6768 | V40 | 2219.173 | 2761.173 |
| V2 | 111.0742 | 631.0742 | V41 | 2274.646 | 2818.646 |
| V3 | 166.5732 | 681.5732 | V42 | 2330.094 | 2875.094 |
| V4 | 222.0468 | 727.0468 | V43 | 2385.593 | 2932.593 |
| V5 | 277.5458 | 777.5458 | V44 | 2441.067 | 2989.067 |
| V6 | 333.0194 | 823.0194 | V45 | 2496.541 | 3046.541 |
| V7 | 388.5184 | 874.5184 | V46 | 2552.04 | 3103.04 |
| V8 | 443.9412 | 919.9412 | V47 | 2607.488 | 3160.488 |
| V9 | 499.4148 | 971.4148 | V48 | 2662.961 | 3216.961 |
| V10 | 554.8884 | 1016.888 | V49 | 2718.435 | 3274.435 |
| V11 | 610.362 | 1068.362 | V50 | 2773.909 | 3330.909 |
| V12 | 665.8356 | 1113.836 | V51 | 2829.382 | 3388.382 |
| V13 | 721.3092 | 1165.309 | V52 | 2884.856 | 3445.856 |
| V14 | 776.7828 | 1210.783 | V53 | 2940.329 | 3502.329 |
| V15 | 832.2564 | 1261.256 | V54 | 2995.803 | 3559.803 |
| V16 | 887.73 | 1306.73 | V55 | 3051.277 | 3616.277 |
| V17 | 943.2036 | 1362.204 | V56 | 3106.776 | 3673.776 |
| V18 | 998.6772 | 1427.677 | V57 | 3162.249 | 3730.249 |
| V19 | 1054.176 | 1488.176 | V58 | 3217.697 | 3787.697 |
| V20 | 1109.65 | 1553.65 | V59 | 3273.196 | 3844.196 |
| V21 | 1165.123 | 1613.123 | V60 | 3328.67 | 3901.67 |
| V22 | 1220.597 | 1678.597 | V61 | 3384.144 | 3958.144 |
| V23 | 1276.071 | 1738.071 | V62 | 3439.617 | 4015.617 |
| V24 | 1331.544 | 1803.544 | V63 | 3495.091 | 4072.091 |
| V25 | 1387.018 | 1863.018 | V64 | 3550.564 | 4129.564 |
| V26 | 1442.491 | 1928.491 | V65 | 3606.038 | 4186.038 |
| V27 | 1497.965 | 2087.965 | V66 | 3661.512 | 4243.512 |
| V28 | 1553.439 | 2053.439 | V67 | 3716.985 | 4299.985 |
| V29 | 1608.938 | 2113.938 | V68 | 3772.459 | 4357.459 |
| V30 | 1664.411 | 2179.411 | V69 | 3827.958 | 4413.958 |
| V31 | 1719.885 | 2239.885 | V70 | 3883.431 | 4471.431 |
| V32 | 1775.358 | 2305.358 | V71 | 3938.905 | 4527.905 |
| V33 | 1830.832 | 2362.832 | V72 | 3994.379 | 4585.379 |
| V34 | 1886.306 | 2419.306 | V73 | 4049.852 | 4641.852 |
| V35 | 1941.779 | 2476.779 | V74 | 4105.326 | 4699.326 |
| V36 | 1997.253 | 2533.253 | V75 | 4160.799 | 4755.799 |
| V37 | 2052.726 | 2590.726 | V76 | 4216.273 | 4813.273 |
| V38 | 2108.225 | 2647.225 | V77 | 4271.747 | 4869.747 |
| V39 | 2163.699 | 2704.699 | V78 | 4327.22 | 4927.22 |

**Table 1b:** Table shows the length of scintillator bars and the optimal length of fibers for the V layer.

| Strip | Length (mm) | WSF length(mm | Strip | Length (mm) | WSF length(mm |
|---|---|---|---|---|---|
| W1 | 55.4482 | 585.6768 | W40 | 2219.071 | 2761.173 |
| W2 | 110.9218 | 631.0742 | W41 | 2274.545 | 2818.646 |
| W3 | 166.3954 | 681.5732 | W42 | 2330.018 | 2875.094 |
| W4 | 221.869 | 727.0468 | W43 | 2385.492 | 2932.593 |
| W5 | 277.368 | 777.5458 | W44 | 2440.991 | 2989.067 |
| W6 | 332.8416 | 823.0194 | W45 | 2496.464 | 3046.541 |
| W7 | 388.3152 | 874.5184 | W46 | 2551.938 | 3103.04 |
| W8 | 443.7888 | 919.9412 | W47 | 2607.412 | 3160.488 |
| W9 | 499.2624 | 971.4148 | W48 | 2662.885 | 3216.961 |
| W10 | 554.736 | 1016.888 | W49 | 2718.359 | 3274.435 |
| W11 | 610.2096 | 1068.362 | W50 | 2773.858 | 3330.909 |
| W12 | 665.734 | 1113.836 | W51 | 2829.331 | 3388.382 |
| W13 | 721.2076 | 1165.309 | W52 | 2884.805 | 3445.856 |
| W14 | 776.6812 | 1210.783 | W53 | 2940.279 | 3502.329 |
| W15 | 832.1548 | 1261.256 | W54 | 2995.752 | 3559.803 |
| W16 | 887.6284 | 1306.73 | W55 | 3051.226 | 3616.277 |
| W17 | 943.1274 | 1362.204 | W56 | 3106.725 | 3673.776 |
| W18 | 998.601 | 1427.677 | W57 | 3162.198 | 3730.249 |
| W19 | 1054.075 | 1488.176 | W58 | 3217.672 | 3787.697 |
| W20 | 1109.548 | 1553.65 | W59 | 3273.146 | 3844.196 |
| W21 | 1165.022 | 1613.123 | W60 | 3328.619 | 3901.67 |
| W22 | 1220.495 | 1678.597 | W61 | 3384.118 | 3958.144 |
| W23 | 1275.944 | 1738.071 | W62 | 3439.592 | 4015.617 |
| W24 | 1331.417 | 1803.544 | W63 | 3495.065 | 4072.091 |
| W25 | 1386.891 | 1863.018 | W64 | 3550.539 | 4129.564 |
| W26 | 1442.39 | 1928.491 | W65 | 3606.013 | 4186.038 |
| W27 | 1497.863 | 2087.965 | W66 | 3661.486 | 4243.512 |
| W28 | 1553.337 | 2053.439 | W67 | 3716.985 | 4299.985 |
| W29 | 1608.811 | 2113.938 | W68 | 3772.459 | 4357.459 |
| W30 | 1664.284 | 2179.411 | W69 | 3827.932 | 4413.958 |
| W31 | 1719.758 | 2239.885 | W70 | 3883.406 | 4471.431 |
| W32 | 1775.257 | 2305.358 | W71 | 3938.88 | 4527.905 |
| W33 | 1830.73 | 2362.832 | W72 | 3994.353 | 4585.379 |
| W34 | 1886.204 | 2419.306 | W73 | 4049.852 | 4641.852 |
| W35 | 1941.678 | 2476.779 | W74 | 4105.326 | 4699.326 |
| W36 | 1997.151 | 2533.253 | W75 | 4160.799 | 4755.799 |
| W37 | 2052.625 | 2590.726 | W76 | 4216.248 | 4813.273 |
| W38 | 2108.124 | 2647.225 | W77 | 4271.747 | 4869.747 |
| W39 | 2163.597 | 2704.699 | W78 | 4327.22 | 4927.22 |

**Table 1c:** Table  shows the length of scintillator bars and the  optimal length of fibers for the W layer.

| Strip | PMT | Strip | PMT | Strip | PMT |
|---|---|---|---|---|---|
| U1 | U1 | U29 | U29 | U57 | U55 |
| U2 | U2 | U30 | U30 | U58 | U55 |
| U3 | U3 | U31 | U31 | U59 | U56 |
| U4 | U4 | U32 | U32 | U60 | U56 |
| U5 | U5 | U33 | U33 | U61 | U57 |
| U6 | U6 | U34 | U34 | U62 | U57 |
| U7 | U7 | U35 | U35 | U63 | U58 |
| U8 | U8 | U36 | U36 | U64 | U58 |
| U9 | U9 | U37 | U37 | U65 | U59 |
| U10 | U10 | U38 | U38 | U66 | U59 |
| U11 | U11 | U39 | U39 | U67 | U60 |
| U12 | U12 | U40 | U40 | U68 | U60 |
| U13 | U13 | U41 | U41 | U69 | U61 |
| U14 | U14 | U42 | U42 | U70 | U61 |
| U15 | U15 | U43 | U43 | U71 | U62 |
| U16 | U16 | U44 | U44 | U72 | U62 |
| U17 | U17 | U45 | U45 | U73 | U63 |
| U18 | U18 | U46 | U46 | U74 | U63 |
| U19 | U19 | U47 | U47 | U75 | U64 |
| U20 | U20 | U48 | U48 | U76 | U64 |
| U21 | U21 | U49 | U49 | U77 | U65 |
| U22 | U22 | U50 | U50 | U78 | U65 |
| U23 | U23 | U51 | U51 | U79 | U66 |
| U24 | U24 | U52 | U52 | U80 | U66 |
| U25 | U25 | U53 | U53 | U81 | U67 |
| U26 | U26 | U54 | U53 | U82 | U67 |
| U27 | U27 | U55 | U54 | U83 | U68 |
| U28 | U28 | U56 | U54 | U84 | U68 |

**Table 2a**: Table shows the correspondence between the scintillator bars and PMTs for the U layer. Adjacent bars are read out by a single PMT for the region highlighted with yellow color.

| Strip | PMT | Strip | PMT | Strip | PMT |
|---|---|---|---|---|---|
| V1 | V1 | V27 | V14 | V53 | V37 |
| V2 | V1 | V28 | V14 | V54 | V38 |
| V3 | V2 | V29 | V15 | V55 | V39 |
| V4 | V2 | V30 | V15 | V56 | V40 |
| V5 | V3 | V31 | V16 | V57 | V41 |
| V6 | V3 | V32 | V16 | V58 | V42 |
| V7 | V4 | V33 | V17 | V59 | V43 |
| V8 | V4 | V34 | V18 | V60 | V44 |
| V9 | V5 | V35 | V19 | V61 | V45 |
| V10 | V5 | V36 | V20 | V62 | V46 |
| V11 | V6 | V37 | V21 | V63 | V47 |
| V12 | V6 | V38 | V22 | V64 | V48 |
| V13 | V7 | V39 | V23 | V65 | V49 |
| V14 | V7 | V40 | V24 | V66 | V50 |
| V15 | V8 | V41 | V25 | V67 | V51 |
| V16 | V8 | V42 | V26 | V68 | V52 |
| V17 | V9 | V43 | V27 | V69 | V53 |
| V18 | V9 | V44 | V28 | V70 | V54 |
| V19 | V10 | V45 | V29 | V71 | V55 |
| V20 | V10 | V46 | V30 | V72 | V56 |
| V21 | V11 | V47 | V31 | V73 | V57 |
| V22 | V11 | V48 | V32 | V74 | V58 |
| V23 | V12 | V49 | V33 | V75 | V59 |
| V24 | V12 | V50 | V34 | V76 | V60 |
| V25 | V13 | V51 | V35 | V77 | V61 |
| V26 | V13 | V52 | V36 | V78 | V62 |

**Table 2b**: Table shows the correspondence between the scintillator bars and PMTs for the V layer. Adjacent bars are read out by a single PMT for the region highlighted with yellow color.

| Strip | PMT | Strip | PMT | Strip | PMT |
|---|---|---|---|---|---|
| W1 | W1 | W27 | W14 | W53 | W37 |
| W2 | W1 | W28 | W14 | W54 | W38 |
| W3 | W2 | W29 | W15 | W55 | W39 |
| W4 | W2 | W30 | W15 | W56 | W40 |
| W5 | W3 | W31 | W16 | W57 | W41 |
| W6 | W3 | W32 | W16 | W58 | W42 |
| W7 | W4 | W33 | W17 | W59 | W43 |
| W8 | W4 | W34 | W18 | W60 | W44 |
| W9 | W5 | W35 | W19 | W61 | W45 |
| W10 | W5 | W36 | W20 | W62 | W46 |
| W11 | W6 | W37 | W21 | W63 | W47 |
| W12 | W6 | W38 | W22 | W64 | W48 |
| W13 | W7 | W39 | W23 | W65 | W49 |
| W14 | W7 | W40 | W24 | W66 | W50 |
| W15 | W8 | W41 | W25 | W67 | W51 |
| W16 | W8 | W42 | W26 | W68 | W52 |
| W17 | W9 | W43 | W27 | W69 | W53 |
| W18 | W9 | W44 | W28 | W70 | W54 |
| W19 | W10 | W45 | W29 | W71 | W55 |
| W20 | W10 | W46 | W30 | W72 | W56 |
| W21 | W11 | W47 | W31 | W73 | W57 |
| W22 | W11 | W48 | W32 | W74 | W58 |
| W23 | W12 | W49 | W33 | W75 | W59 |
| W24 | W12 | W50 | W34 | W76 | W60 |
| W25 | W13 | W51 | W35 | W77 | W61 |
| W26 | W13 | W52 | W36 | W78 | W62 |

**Table 2c**: Table shows the correspondence between the scintillator bars and PMTs for the W layer. Adjacent bars are read out by a single PMT for the region highlighted with yellow color.

## E. Procedures for measuring the light transmission characteristics of the scintillator-fiber system.

In order to achieve a uniform response over the area covered by the PCAL, the transmission properties of the scintillator bars needs to be characterized. To minimize the data acquisition time, we will measure the PMT anode average current produced as a result of the irradiation of a radioactive source ($^{90}Sr$ beta source) at different positions of the scintillator bar. For the first sector, we will do the measurements for all of the longest (>200 cm) scintillator bars. The apparatus consists of a PMT to measure the response of the scintillator-fiber system and a radioactive source, which is mounted on a holder that is positioned on the top of a system that can be moved automatically along the length of the scintillator strip (see Figure 7 below).

Work described below requires two persons.

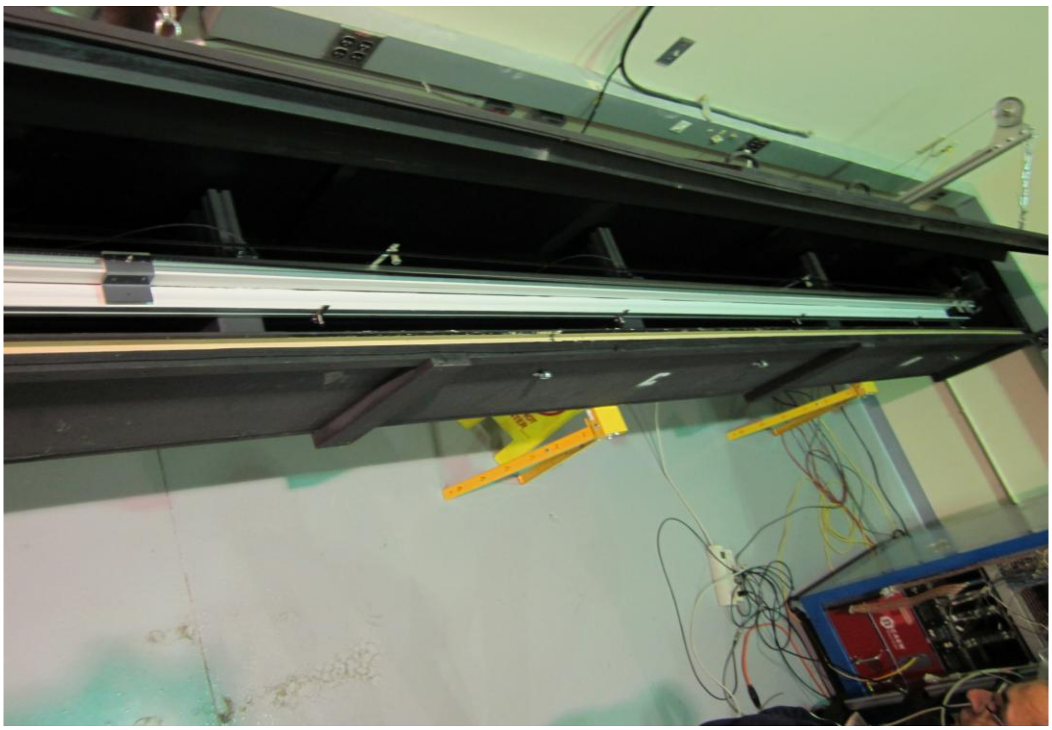

**Figure 7: Figure shows the setup inside the light tight box.**

a) Begin with the longest scintillator strip for a given sector, view and layer.
b) Visually inspect the scintillator strips to make sure that the scintillator strips are in good condition.
c) Make sure that the holes in the strips are clean. To do this, place the scintillator strip on the staging table. Insert the long stainless steel wire in to the hole; make sure to shake the wire to remove the specks or dust that may be in the holes. Repeat this for the other hole also. Then blow air through the hole for the final cleaning.
d) Once the cleaning is done carefully insert test fibers into the scintillator (two fibers per hole). These fibers need special attention; we don't want any kind of scratch on the fibers since the light output depends on the condition of these test fibers. Also, note that these fibers are glued to a plastic adapter; during measurements one side of the adaptor is going to be in contact with the photocathode of the PMT. So the adaptor also needs to be handled carefully.
e) Place the scintillator-fiber assembly on the setup in the dark box. Make sure the edge of the scintillator coincide with the zero marking on the aluminum profile. Make sure that the extra fiber on the far end of scintillator is also resting on the aluminum profile.
f) Push the adaptor into the PMT housing and make sure that it touches the photocathode. Secure the PMT.
g) Close the dark box, visually inspect that the box is closed properly.
h) Switch on the HV and raise it to 1000V
i) In the graphical interface, input the sector, layer, view and scintillator number from the drop down menu. Program creates a unique output file based on these information.
j) Select the step size (usually 10 cm) and press start. Inside the dark box, the source will move automatically to different positions along the length of the scintillator. The Keithley multimeter will collect 500 readings (this number can be changed in the GUI) of the PMT anode current at a given source position; the average and the standard deviation of the measurements will be recorded to the output file for each position of the source together with the position value.
k) The dark current is also recorded to the output file. The reading recorded when source passes the far end of the strip is the dark current. This is the last reading in the output file.
l) Switch off the HV once the measurement is finished.
m) Open the dark box, detach the adapter from the PMT. Carefully take the scintillator and fiber system to the staging table.
n) Carefully remove the fibers from the tested scintillator strip.
o) Move the tested scintillator to the storage shelf.
p) One can check the data collected for the previous scintillator while the measurement is going on for the next strip. To do this, open paw (in the directory where the GUI is located) and type exe plot_pmtcurr file_name (replace file_name with the name of the data file). Make sure PMT current has its typical exponential dependence on source position and the response is uniform. Also make sure that the dark current displayed on the top of the graph is reasonable.

q) Repeat steps *a to p* for the next strip

*Note: Make sure that appropriate training is completed since radioactive source is involved in the measurement. Handling of the materials requires use of gloves. If you need to open the dark box during the measurement, make sure that the HV is turned off.*

## F. Fiber testing procedures.

We will use the same setup used for scintillator tests for the testing of fibers also. First, visually inspect and make sure that all fibers are in good condition and there are no broken fibers. Handling of fibers needs special attention and extreme care. To minimize exposure (and hence avoiding dirt from outside), only minimum length of fibers should be taken out of the plastic wrapper for the tests described here. For light transmission measurements select four fibers at a time.

Work described below requires two persons

a) Open both ends of plastic cover which contains the fibers. Keep the plastic cover in the middle portion which will act as a protective cover. Only minimum length of fibers from both ends should be taken out of the plastic cover for the tests.
b) Select four fibers from the bunch.
c) Insert the selected fibers through the holes in plastic adaptor.
d) Insert the other end of the selected fibers to the test scintillator (test scintillator is only about 30cm long). For consistency, adjust the length of the fibers so that the fibers are just enough to cover full length of the test scintillator.
e) Keep this scintillator-fiber system (about halfway through) under the radioactive source, which is parked at the far end from the PMT side. For consistency, make sure that the distance between source and PMT is same for all the measurements.
f) Close the dark box, visually inspect that the box is closed properly.
g) We will do one measurement on the scintillator-fiber system and one to measure the dark current. Using the GUI which control Keithely multimeter, record the PMT anode current. The average, standard deviation of the measurements as well as the dark current will be recorded to the output file.
h) Switch off the HV once the measurement is finished.
i) Open the dark box, detach the adapter from the PMT and take out the tested fibers from the adaptor.
j) If the average PMT anode current is less than 15% of the nominal value, separate this bunch of fibers from the rest.
k) Try to carefully inspect the above fibers one at a time, it may be that one fiber is broken or bad and the other three are good. If you can’t visually identify the bad fibers, use different combinations of these fibers along with fibers from the new bunch. Remove the bad fiber(s) from the rest.
l) Repeat the step (a) to (i) for next bunch of fibers.

## G. Procedures for cutting scintillator strips.

Scintillator strips for PCAL were ordered and received in two lengths, 420 cm (1450 strips) and 450cm (2710 strips). Since the PCAL layer has an isosceles triangular shape, strips in a layer have different lengths and ends of strips must be cut in an angle. The shorter strips are to be cut for U-view, the longer strips are for V- and W-views.

The shorter strips are to be cut for U-view, the longer strips are for V- and W-views. Strips in U-view (perpendicular to the beam direction) have the same angle cut at both ends, $27.1^{o}$. One end of V- and W-strips has $27.1^{o}$ angle cut, while the second end has $35.8^{o}$ angle cut.

To cut the scintillator strips to the right length and angle, method proposed by FNAL-NICADD group, a radial arm saw and a 10'' 80 teeth C4 wood saw blade, is used. A long cutting table was build based on Delta RS830 10'' radial arm saw to handle the longest PCAL strips. As a base for the table a frame made of Bosch Rexroth aluminum profiles is used. Two, 90 degree long profiles were used to support wood plates as a tabletop, see Figure 5 and Figure 6. The back of the profile, closest to the saw's mounting point, was used to alight strips and saw. Two trapezoidal shape plates from ½ inch aluminum were machined for alignment of the saw blade and the end of scintillator strips for cutting. Aluminum trapezoids have one of sides perpendicular to the parallel sides, while second side formed exact angle required for the cutting ($27.1^{o}$ or $35.8^{o}$). Parallel sides were made long enough to give required level arm for the correct alignment of the saw blade and the scintillator ends against the profile.

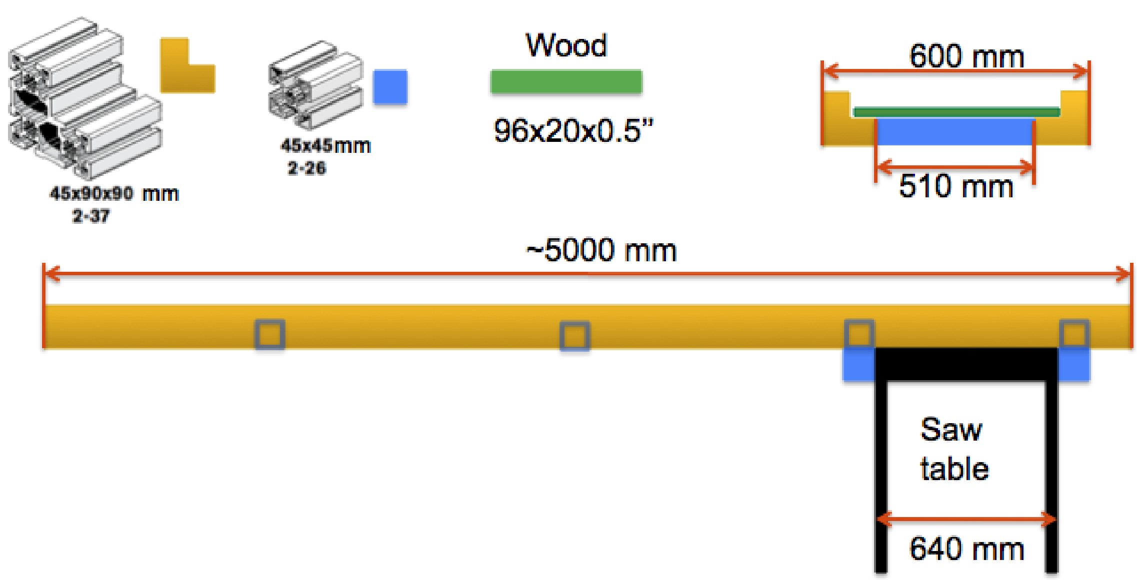

**Figure 5: Schematics of the cutting table**


**Figure6: Picture of the cutting table. The radial arm saw is mounted on the table.**

Scintillators are cut 5 at the time. The value of the lengths for each strip is given for the longest side. Required accuracy for the strip length is ±1 mm. Length of the strips are measured using a tape measure attached to the aluminum profile at the back of the table. Two PCAL strips are cut from each original strip. Each original strip is labeled from both ends. After cutting, each PCAL strip is labeled to indicate module, layer and the strip number. Records are kept on correspondence of the original (FNAL) and the new (PCAL) labels.

Following are the steps for cutting the scintillator strips for U-view:

a. Align the saw blade against the long Bosch Rexroth profile using machined aluminum plates and set the angle in a way that longest cut is towards the back of the table.

b. Place all the strips for the whole layer on the bench and measure average width. Recalculate length of strips corresponding to the average length using exact value of cut angles.
c. Set five scintillator pieces on the table and press them against the back wall of the table (against aluminum profile).
d. Align ends that in the way that only ~5 cm will be cut-out from the ends.
e. Push and secure strips against tabletop with screwed-in handle and make a cut.
f. Release strips and flip them, lengthwise, and put them on the table without changing the order.
g. Using tape-measure position the end of the strip closest to the profile (back wall) in correct distance from the blade.
h. Push the alignment plate towards the end of the strip and secure it. Make sure strip will not move.
i. Put rest of the strips against the plate and against the first strip. Check the position of the first strip again, if strip is moved, reposition.
j. Push and secure strips against the tabletop and make a cut.
k. Release strips, part of the strips that are on the long side of the table now ready, they have right length and angles.
l. Clean ends from burred, surfaces from debris, label and move strips to the storage.
m. Cut out part of the strips now have one end with correct angle.
n. Move cutout strips to the table, flip each one along their axis, and change the order on the table (farthest from the back wall now will become the closest to the back wall).
o. Repeat steps f to k.

**Note:**

Most of the work discussed in this document needs relatively clean environment. Also, handling of the materials requires use of gloves. Additional, procedure specific safety instructions are included in the relevant sections.