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**Abstract**

We have studied light yield and uniformity of the light collection of large scintillator tiles with WLS fiber read-out. The results indicate that large (50 cm $\times$ 50 cm) tiles have light yield of more than 2 photoelectrons per minimum ionizing particle and a very good transverse uniformity of the response. Such tiles met design criteria for the Hadron Calorimeter for the SDC Barrel detector. The results of this study would be also applicable to the CMS hadron detectors at LHC.

## 1 Introduction

In this note we describe the measurements of tile/fiber assemblies built according to the specifications of the SDC Barrel Hadron Calorimeter. We have used 4 mm thick SCSN-38 from Kuraray [1] as a scintillator material. The light from the tiles was collected by a 0.83 mm diameter WLS fiber Y11(200) [1], multiclad S-type from Kuraray, spliced [3] to 0.83 mm diameter, multiclad clear Kuraray fiber. The tile edges were painted with white reflective paint BC-620 from Bicron [2], and wrapped with white reflective material Tyvek [4].

The absolute light yield and uniformity of the response of tile/fiber assemblies were measured using the collimated $Ru^{106}$ $\beta$ source scanner. The relative light yield of various tiles was measured using the $Cs^{137}$ $\gamma$ source setup. The detailed description of the experimental setup can be found in our previous note [5].

[1] The numbers in the parentheses correspond to number of parts per million (ppm) by weight of a fluorescent dye in the fiber core.

| layer number | tile size | length of WLS fiber | length of clear fiber |
|---|---|---|---|
| 01 (first HAC1) | 25.0 cm | 83 cm | 180 cm |
| 20 (center HAC1) | 30.0 cm | 103 cm | 130 cm |
| 32 (last HAC1) | 40.0 cm | 142 cm | 100 cm |
| 44 (last HAC2) | 50.0 cm | 176 cm | 50 cm |

Table 1: Approximate sizes of tiles of few selected layers of Hadron Barrel calorimeter.Tile sizes correspond to transverse segmentation $\Delta\eta \times \Delta\phi$ of $0.1 \times 0.1$ .

## 2 Tile sizes for the SDC Barrel Calorimeter

The sizes of hadron tiles in the central $\eta$ tower of the SDC Barrel calorimeter [6], vary from approximately 23.5 cm × 23.5 cm (9 1/4 inches × 9 1/4 inches) for the first layer of the HAC1 to approximately 50.0 cm × 50.0 cm (20 inches × 20 inches) for the last layer of the HAC2 [2]. Table 1 lists the tile sizes of few selected layers for the central $\eta$ tower of the hadron calorimeter. It also indicates the length of WLS fibers needed for the read-out, as well as the length of clear fibers carrying the light from the edge of the tiles to photomultipliers located approximately 50 cm behind the HAC2 detector.

## 3 Absolute light of the 50 cm × 50 cm tiles with various fiber read-out patterns

We have compared the absolute light yield of 50 cm × 50 cm tiles using four different fiber read-out patterns. The tiles had a single groove encircling their perimeter, with the distance between the tile edges and the center of the fiber groove equal to 3 mm ($\approx$ 1/8 inch). The depth of the groove was equal to 2 mm (0.080 inch).

Figure 1 shows a schematic drawing of various patterns of the fiber read-out studied in this note. The read-out patterns differed in the number of fibers laid in the groove (one or two WLS fibers) and whether one or both of the ends of WLS fibers were spliced to clear fibers connecting to a photomultiplier (PMT):

- $1\sigma$ pattern: Only one WLS fiber was laid in the fiber groove. One of the ends of WLS fibers was spliced to 50 cm long clear fiber and connected to the PMT. The other end of the fiber was mirrored [7] and terminated inside the tile;

[2]The SDC Barrel Hadron Calorimeter would consist of 32 layers with 1 inch iron sampling (HAC1), followed by the 12 layers with 2 inch iron sampling (HAC2).

| fiber pattern | # of fibers to PMT | abs. l. yield[PE/mip] | l. yield rel to $1\sigma$ |
|---|---|---|---|
| $1\sigma$ | 1 (mirrored) | 2.3±0.1 | 1.00 |
| $2\sigma$ | 2 (mirrored) | 3.4±0.2 | 1.50 |
| $1\alpha$ | 2 | 3.3±0.2 | 1.43 |
| $2\alpha$ | 4 | 5.4±0.2 | 2.35 |
| $2G$ (Fig. 4) | 2 (mirrored) | 2.6±0.2 | 1.15 |

Table 2: Light yield of 50 cm × 50 cm SCSN-38, 4 mm thick tile with various fiber read-out patterns. The absolute light yield is expressed in number of photoelectrons per minimum ionizing particle (PE/mip).

- $2\sigma$ pattern: Two WLS fibers were laid in the groove, each fiber was connected to the PMT via a single, 50 cm long clear fiber. The other ends of WLS fibers were mirrored and terminated inside the tile;
- $1\alpha$ pattern: Only one WLS fiber was laid in the fiber groove. However in this case both ends of the WLS fiber were spliced to 50 cm long clear fibers and connected to the PMT.
- $2\alpha$ pattern: Two WLS fibers were laid in the fiber groove, with all four ends of the WLS fibers spliced to 50 cm long clear fibers and connected to the PMT. In this case total of four clear fibers were carrying the light from the tile to the PMT.

Figure 2 shows the ADC pulse height spectrum for the 50 cm × 50 cm tile read out using the $2\sigma$ fiber pattern. The fraction of triggers with no pulse height was equal to 3.5 ± 0.1%, corresponding to the absolute light yield of the tile of 3.4± 0.1 photoelectrons per minimum ionizing particle.

Figure 3 presents the light yield of the 50 cm × 50 cm tiles as a function of fiber read-out pattern. The highest light yield corresponds to the $2\alpha$ pattern, with four clear fibers connected to the PMT. The results indicate that light yield of large tiles can be increased by factor of 1.5 by introducing an additional WLS fiber into the groove. The results are also summarized in Table 2.

It is important to note that in the case of the $2\sigma$ and $2\alpha$ patterns, the second WLS fiber was inserted into the same groove [3] as the first one, (see Fig. 1). In addition to the patterns described above, we have studied a tile with two mirrored WLS fibers inserted into parallel grooves, each 1.5 mm deep, separated by a 3 mm spacing. Figure 4 shows the schematic diagram of the fiber groove layout (pattern $2G$) for such a tile. The light yield of the tile with fibers inserted to two separate grooves was only 15% higher than the light yield of the tile read out only by the single WLS fiber, ( the $2G$ vs $1\sigma$ fiber read-out patterns).

[3]The depth of the groove was 2 mm. appropriate to accommodate two 0.83 mm diameter fibers.

It has been demonstrated earlier [9], that one can correct for some back-leakage of the energy from late interacting particles in a hadron calorimeter by increasing the relative light yield of the layers at the back of the hadron calorimeter. The results from the Hanging File Calorimeter [10] indicated that a factor of $\approx 1.8$ for last interaction length of the detector should be applied. If the $1\sigma$ fiber read-out pattern is used as a standard for most of the layers of the SDC Hadron Barrel detector, then the $2\sigma$ fiber read-out pattern for the last three layers of HAC2 ($\approx 1\ \lambda_{INT}$) would allow one to achieve proper exit-weighting.

# 4 Transverse uniformity of 50cm $\times$ 50cm tiles

We have studied the transverse uniformity of light collection of the 50 cm $\times$ 50 cm tile with the $2\sigma$ fiber read-out pattern, using the collimated $\beta$ source setup. Figure 5 shows a plot of transverse scan of the tile. The uniformity of the response (r.m.s./mean response of the tile) is better than 5%. A similar result was achieved for the tile with $1\sigma$ fiber read-out pattern.

# 5 Relative light yield of tiles from selected layers of HAC1 and HAC2 Barrel Calorimeter

We have compared the absolute light yield of selected SDC Hadron Barrel calorimeter tiles using a collimated $\beta$ source measurement. Figure 6 shows the absolute light yield for layer 1, layer 20, layer 32 (HAC1 compartment) and layer 44 (HAC2 compartment), plotted as a function of the depth of the calorimeter expressed in inches of iron absorber. The tiles were read out using the $1\sigma$ fiber pattern. Tile sizes and length of clear fibers used in this measurement are defined in Table 1.

As we have reported in our previous note [5] , one expects the relative light yield of different size tiles to scale with variable $l/A$, where $l$ is the length of the WLS read-out fiber inside the tile and $A$ is the area of the tile. Additionally the relative light yield of the tiles depends on the length of the clear fibers between the tile's edge and the PMT [4]. The dashed line on Fig. 6 indicates the predicted dependence of the relative light yield of the tiles, including both the $l/A$ dependence as well as the light attenuation effect due to various length of clear fibers. Table 3 summarizes the comparison between the light yield measurements of tiles from selected HAC1 and HAC2 layers and the predicted light yield dependence. The data is in fair agreement with the predicted dependence.

Earlier,we have reported [8] on the degradation of the energy resolution of hadron calorimeters due to systematic variation in the light yield of tiles belonging to same read-out towers.

[4] The attenuation length of clear Kuraray fiber is $\lambda_{cl} \approx 700$ cm.

| layer number | abs. light yield | rel. light yield | $l/A$ scaling $\times$ $exp-(\Delta L_{cl}/\lambda_{cl})$ |
|---|---|---|---|
| 01 (first HAC1) | $3.6 \pm 0.1$ | 1.6 | $2.04 \times 0.83 = 1.69$ |
| 20 (center HAC1) | $3.5 \pm 0.1$ | 1.5 | $1.58 \times 0.89 = 1.41$ |
| 32 (last HAC1) | $2.6 \pm 0.1$ | 1.13 | $1.33 \times 0.93 = 1.24$ |
| 44 (last HAC2) | $2.3 \pm 0.1$ | 1.0 | $1.00 \times 1.00 = 1.00$ |

Table 3: Light yield of various HAC1 and HAC2 tiles. The table summarizes the absolute light yields of tiles expressed in PE/mip (column 2) and light yield relative to last HAC2 tiles (column 3). Column 4 of the table shows the value of predicted variation in the light yield of the tiles using $l/A$ scaling and effect of attenuation of light in clear fibers.

The study indicated that a 20% decrease in the relative light yield between the front and back layers of the calorimeter would lead to the increase in energy resolution for 100 GeV pions by a factor of 1.15. Note that in case of the SDC detector, the HAC1 (layers 1 - 32) and HAC2 (layers 33-44) compartments would be read out by separate phototubes and have individually adjustable gains. An approximately 25% front-to-back slope within the HAC1 and HAC2 compartments separately, could be corrected by using selective masking technique [11] at the phototube face.

An independent method of equalizing the light yield of tiles has been developed by the CDF Plug Upgrade group [12]. In this method, the absolute light yield of tiles in each layer was adjusted by changing the distance between the edge of the tile and the fiber groove, thus affecting the value of $l/A$ parameter. In addition, the light yield of tiles was be adjusted by extending the length of WLS fibers past the edge of the tile. and thus varying the location of the splice between WLS and clear fibers. The adjustment allowed us to change the effective attenuation of light in the fibers carrying light to the PMT. Combination of $l/A$ and attenuation techniques allowed us to control the front-to-back slope of tiles in the upgraded CDF Plug Hadron calorimeter at the level of $\pm$ 10%.

# 6 Effects of variation of the pulse height integration time

We have studied the effect of the variation of the ADC gate length on the response of the large hadron tile (50 cm $\times$ 50 cm) as well as typical EM tile (10.8 cm $\times$ 10.8 cm). The standard length of the ADC gate was equal to 60 nanoseconds (ns) [5]. In this study, we have varied the ADC gate length from 40 ns to 100 ns. The response of the tile was determined by averaging the pulse height spectrum digitized by the ADC unit.

[5] The phototube signal from the tiles was timed in so that it would arrive about 10 nanoseconds after the rising edge of the ADC gate, as required by the Le Croy ADC 2249A.

| | |
|---|---|
| scintillator material | SCSN38 |
| scintillator thickness | 4 mm |
| fiber groove depth | 2 mm |
| radius of fiber grooves | 3 cm |
| tile edge-fiber groove sepa | 3 mm |
| tile edge treatment | white paint BC-620 |
| tile wrapping | Tyvek 1055B |
| WLS fiber material | Y11(200) |
| WLS fiber diameter | 0.83 mm |

Table 4: Summary of the design parameters of the scintillator tiles for the SDC Barrel Hadron Calorimeter.

Figure 6 shows the response of the tiles, as a function of length of ADC gate. By shortening the length of the ADC gate from 100 ns to 40 ns, the relative response of the tiles decreased by approximately 10%.

## 7 Design of the SDC Hadron Barrel Calorimeter tiles

In Table 4 we have summarized the design parameters of the SDC Hadron Barrel Calorimeter tiles.

## 8 Acknowledgements

We wish to thank many technical staff members of the Fermilab Physics Department and the Technical Support Services who helped us conduct this R&D project. This work was in part supported by the Department of Energy, Grant No. DE-FG02-91ER40685 (U. of Rochester) and Contract No. DE-AC02-76CHO3000 (Fermilab).

## References


[1] Kuraray International, 200 Park Ave., New York, NY 10166.

[2] Bicron Inc., 12345 Kinsman Rd., Newbury OH 44065-9677.

[3] C. Bromberg et al., New Methods in Optical Fiber Preparation for Scintillating Tile Calorimetry in CDF, to be published in the proceedings of the IV International Conference on the Calorimetry in the High Energy Physics, La Biodola, Elba, Sept. 1993.

[4] Tyvek is a trademark of a white reflective material produced by the Du Pont Co. E.I. Du Pont de Nemours & Co., Fibers Department, Chestnut Run Plaza, PO Box 80,705, Wilmington, DE 19880-0705. Here we have used 1055B 'Housewrap' Tyvek.

[5] P. de Barbaro et al., Recent R&D Results on Tile/Fiber Calorimetry, University of Rochester preprint UR-1299, SSC-SDC Note 1993-407, January 1993.

[6] M. Banas, private communication.

[7] Mirroring was performed in the Fermilab Physics Dept. facility. The reflectivity of mirrors was measured previously [5] to increase the light yield of tiles by the factor 1.4

[8] P. de Barbaro, A. Bodek, and B. Winer, The effects of tile miscalibrations on the performance of the tile/fiber based hadron calorimeters, University of Rochester preprint UR-1301, January 1993.

[9] L. W. Jones, "Calorimeter Truncation", UM HE 91-26 (Jan. 1991)
L. W. Jones, "Reduction of Calorimeter Depth by Weighting Last Layer", UM HE 91-27 (Jul. 1991)

[10] A. Beretvas et al., Beam Tests of Composite Calorimeter Configurations from Reconfigurable-Stack Calorimeter, Nucl. Instr. and Methods, A329, 50 (1993).

[11] R. Kadel, private communication.

[12] P. de Barbaro et al., CDF Plug Upgrade Hadron Calorimeter Design, CDF Note 2545, April 1994.

Figures

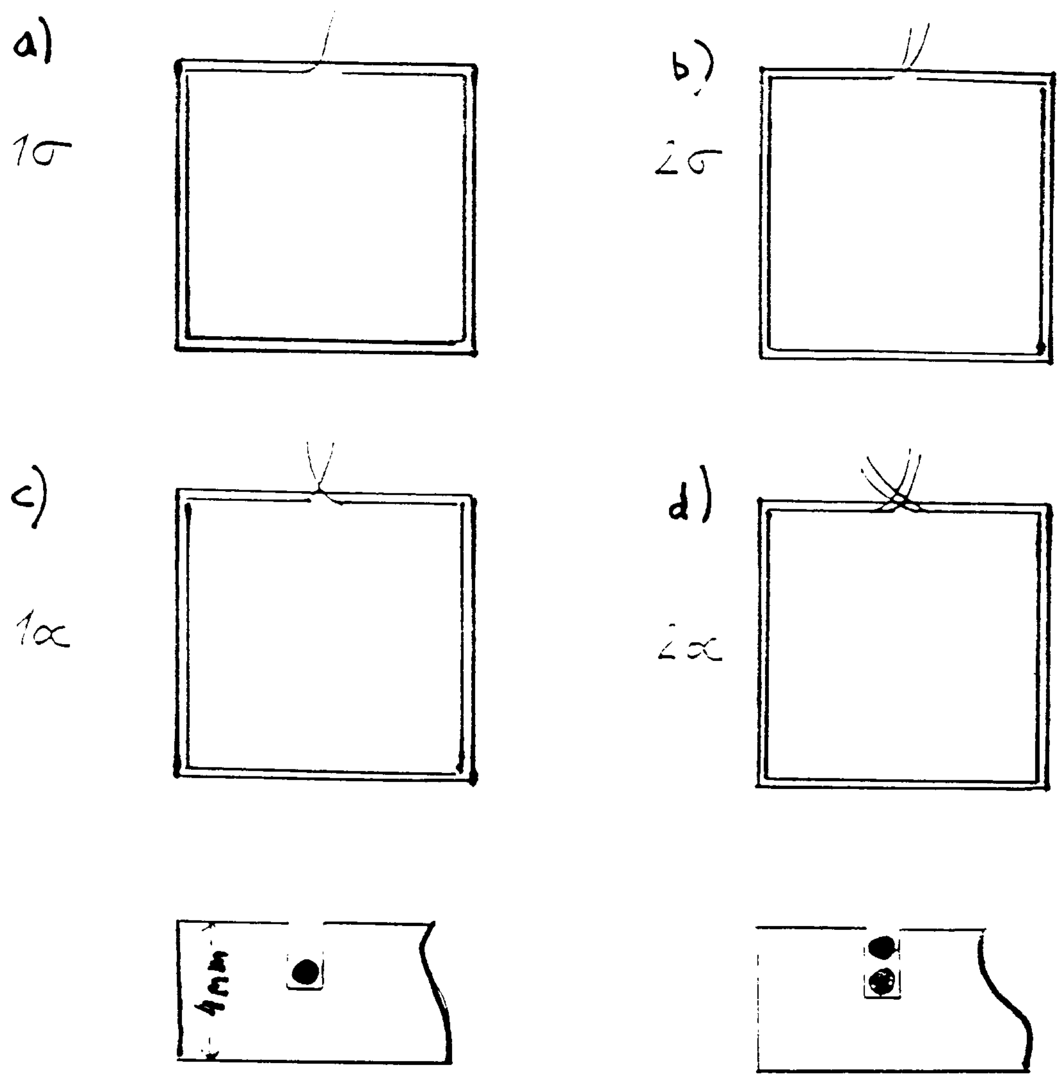


Figure 1: Schematic diagram of different fiber read-out patterns studied in this note.

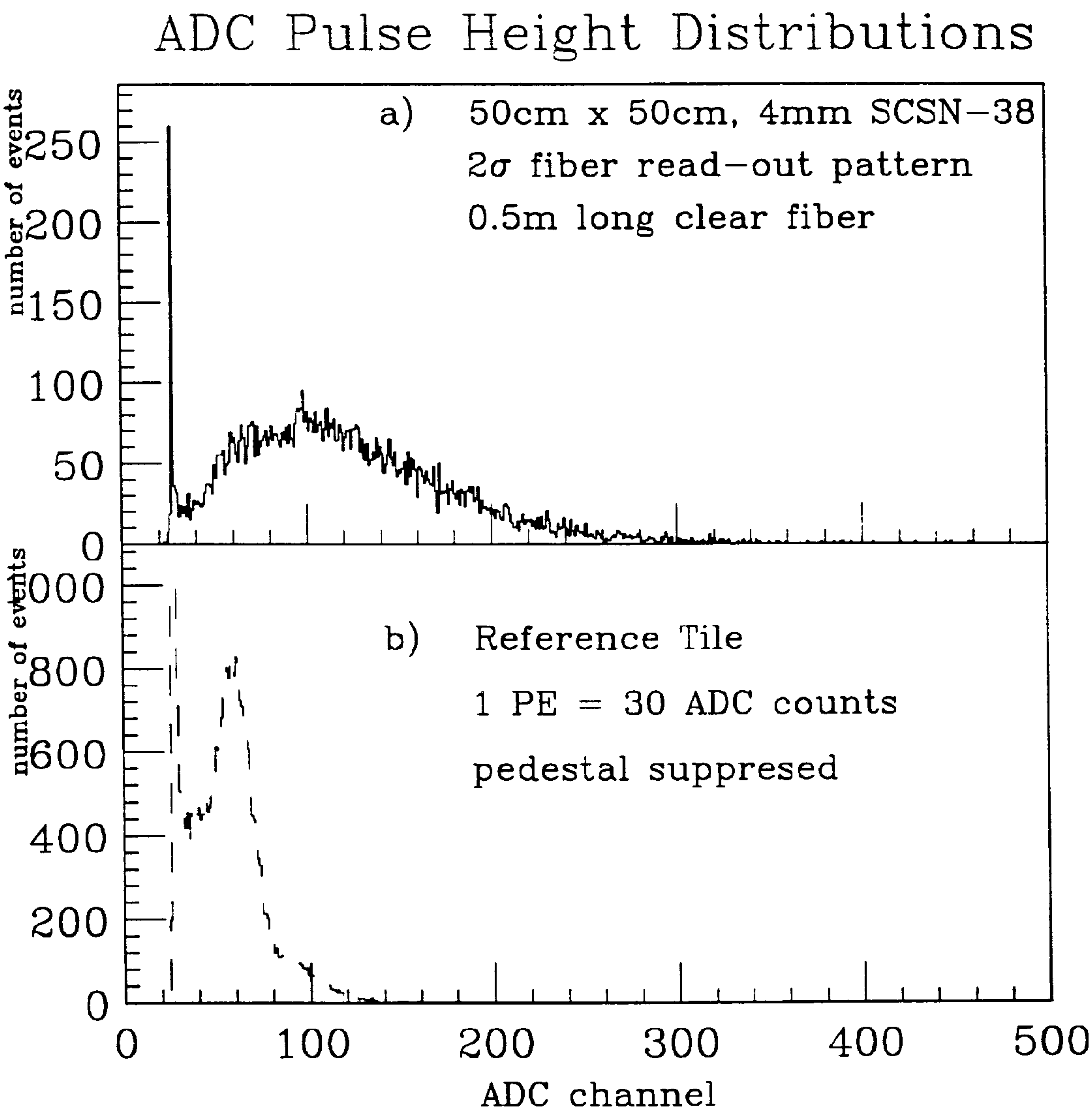


Figure 2: ADC pulse height spectrum for tiles using electrons from collimated $\beta$ source:
a) ADC spectrum for the tile built using 4mm thick SCSN-38 scintillator. The transverse size of the tile is 50 cm $\times$ 50 cm, read out with the $2\sigma$ WLS fiber pattern (see Fig 1b). The edges of the tile were painted with white reflective paint BC-620 from Bicron. Light was collected using 0.83 mm diameter Y11(200) multiclad WLS fiber from Kuraray, spliced to 0.5 m of multiclad clear Kuraray fiber. One of the ends of the WLS fibers were terminated inside the tile and were mirrored using the sputtering technique. The tile was wrapped using Tyvek 1055B material by Du Pont. The fraction of triggers with no ADC deposition is equal to $3.5 \pm 0.1$ % corresponding to the average light yield of $3.4 \pm 0.1$ photoelectrons per minimum ionizing particle (PE/mip).
b) ADC spectrum for the reference tile. The light yield of this tile is $\simeq 0.3$ PE/m.i.p. The position of the one-photoelectron peak was used to determine the number of ADC counts per 1 PE.

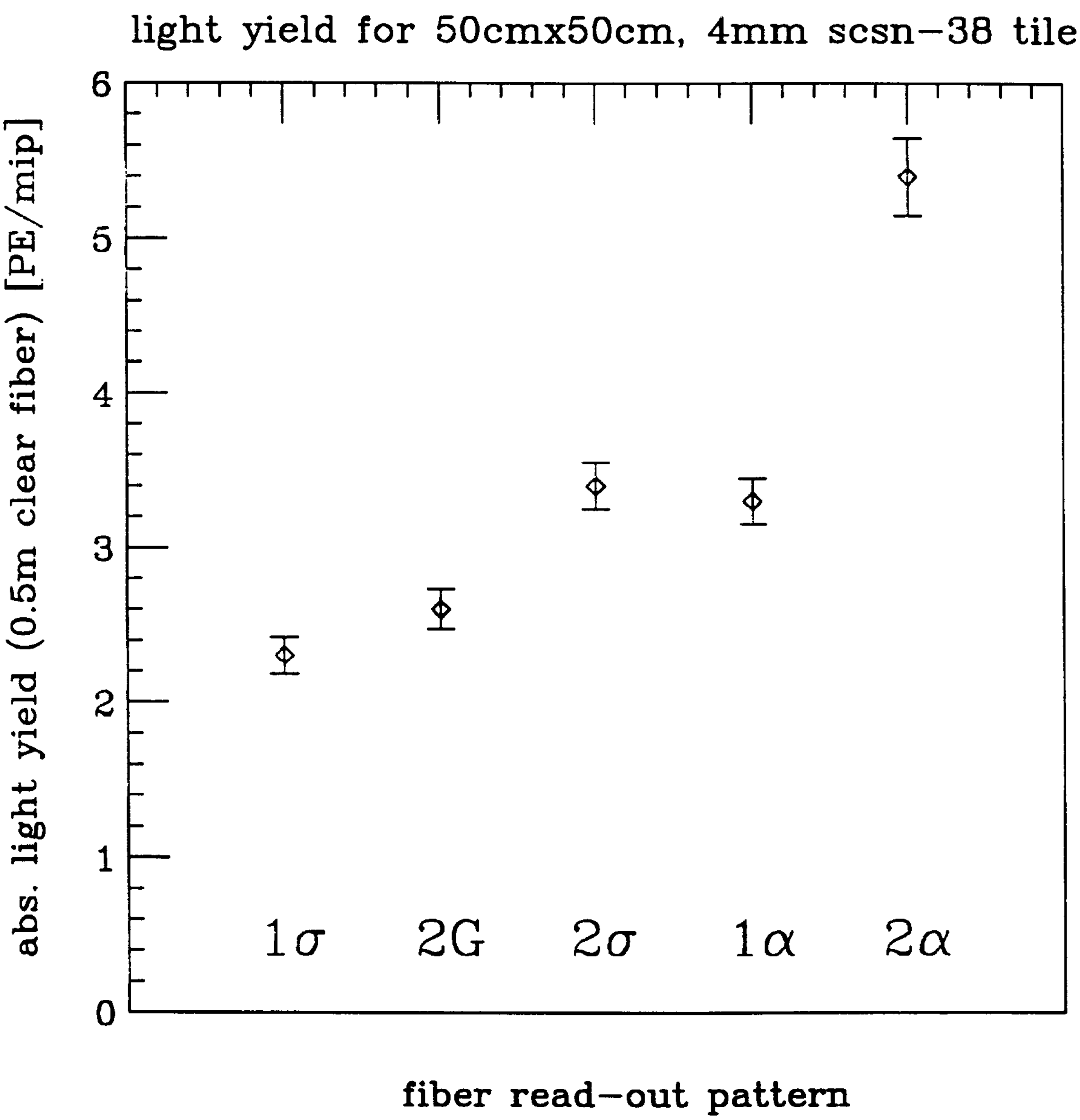


Figure 3: The absolute light yield of the 50 cm × 50 cm tile as a function of various patterns of the fiber read-out. The patterns are depicted on Fig. 1 ( patterns $1\sigma$, $2\sigma$, $1\alpha$ and $2\alpha$) and Fig. 4 ( pattern $2G$).

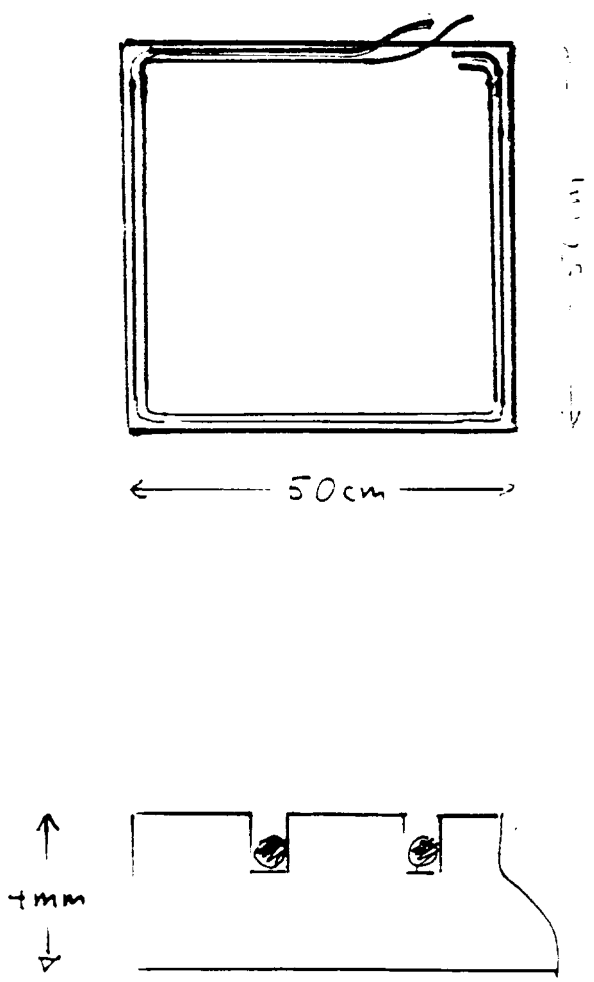


Figure 4: Schematic diagram of a fiber layout using two parallel grooves, separated by 3mm, pattern $2G$.

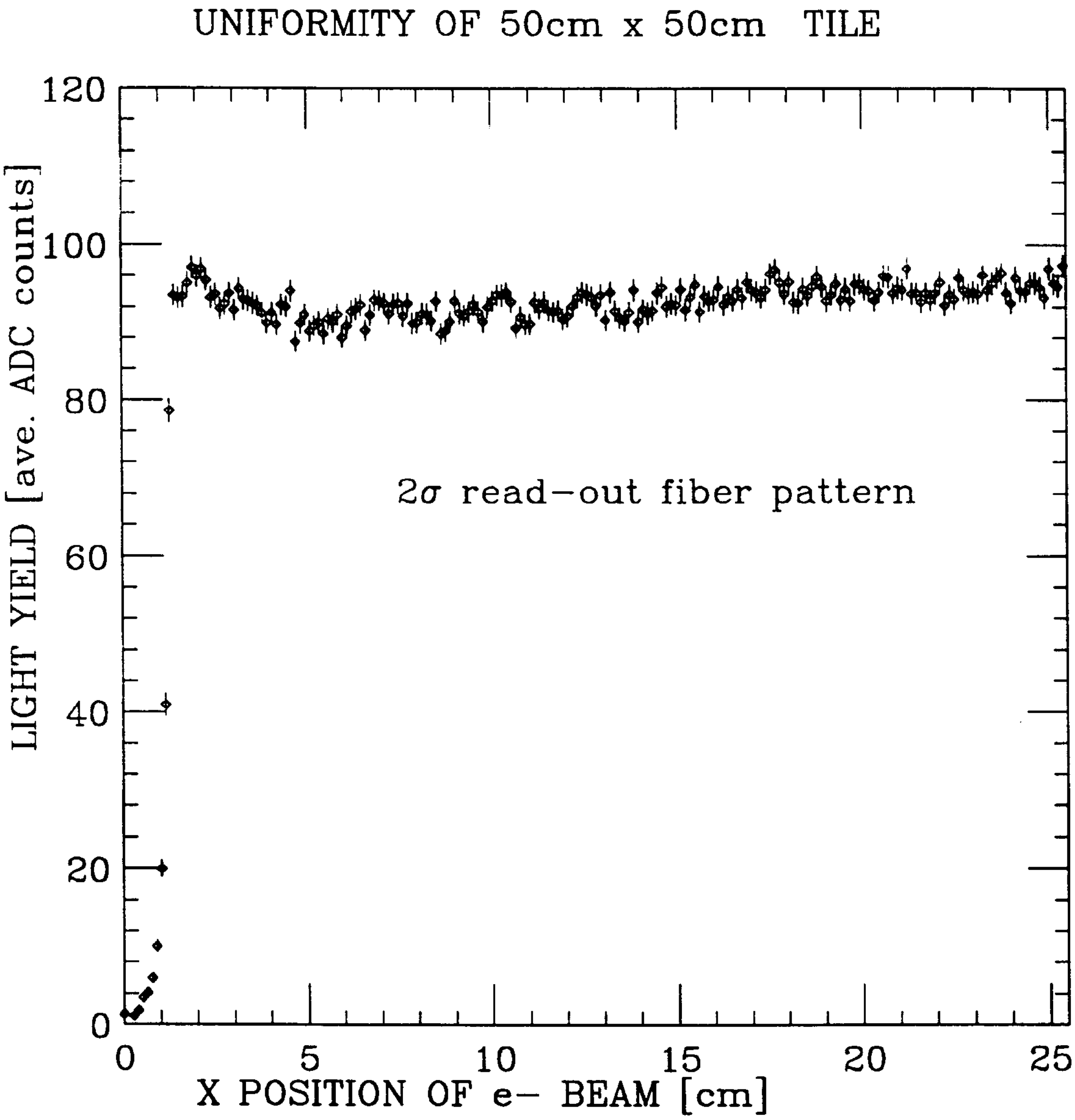


Figure 5: The scan of 50 cm $\times$ 50 cm tile using collimated $\beta$ source. Due to the size limitations of the scanner box, the data corresponds to a single scan of a section of the tile.

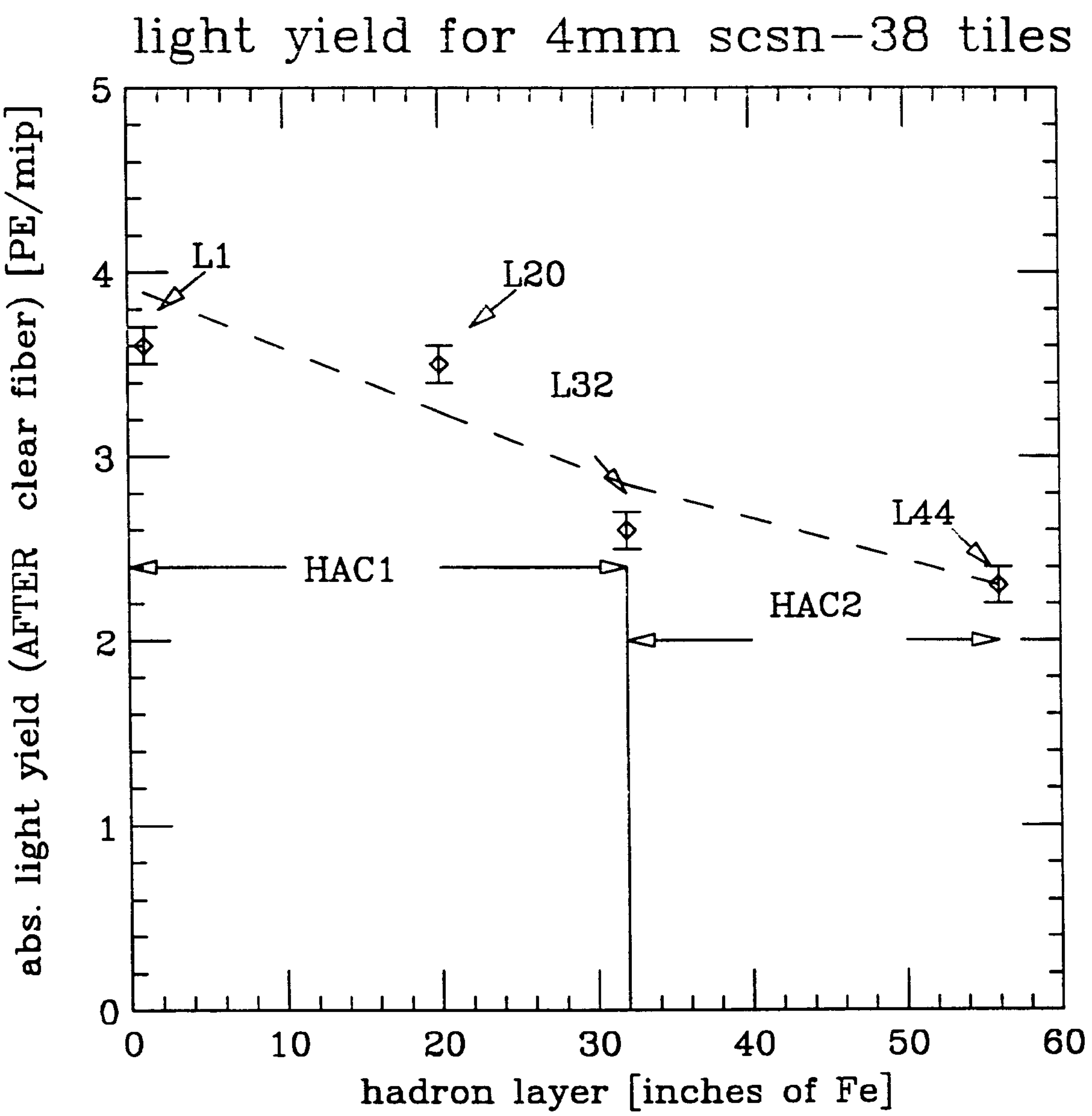


Figure 6: The absolute light yield of the selected tiles of the central $\eta$ tower. The tiles were read out using the $1\sigma$ fiber read-out pattern, as shown on Fig. 1a. The data points were measured using the collimated $\beta$ gun. HAC1 compartment corresponds to first 32 inches of Fe. HAC2 compartment covers the remaining back portion of the calorimeter. Note that HAC1 and HAC2 would be read out by different phototubes with individually adjustable gains. The dashed line indicates the predicted dependence of the relative light yield of the tiles. The prediction includes both the change in the size of the tiles ( relative light yield scales with the variable $l/A$, where $l$ is the length of WLS fiber inside the tile, and $A$ is the area of the tile) and the variation in the attenuation of light due to difference in the length of the clear fibers for various layers, ($\approx exp-(\Delta L_{cl}/\lambda_{cl})$, where $\Delta_{cl}$ is the difference in the length of clear fibers and $\lambda_{cl}$ is the attenuation length of clear fiber). The predicted curve was calculated assuming $\lambda_{cl}$=700 cm, and was normalized to the data point for the last HAC2 tile (layer # 44).

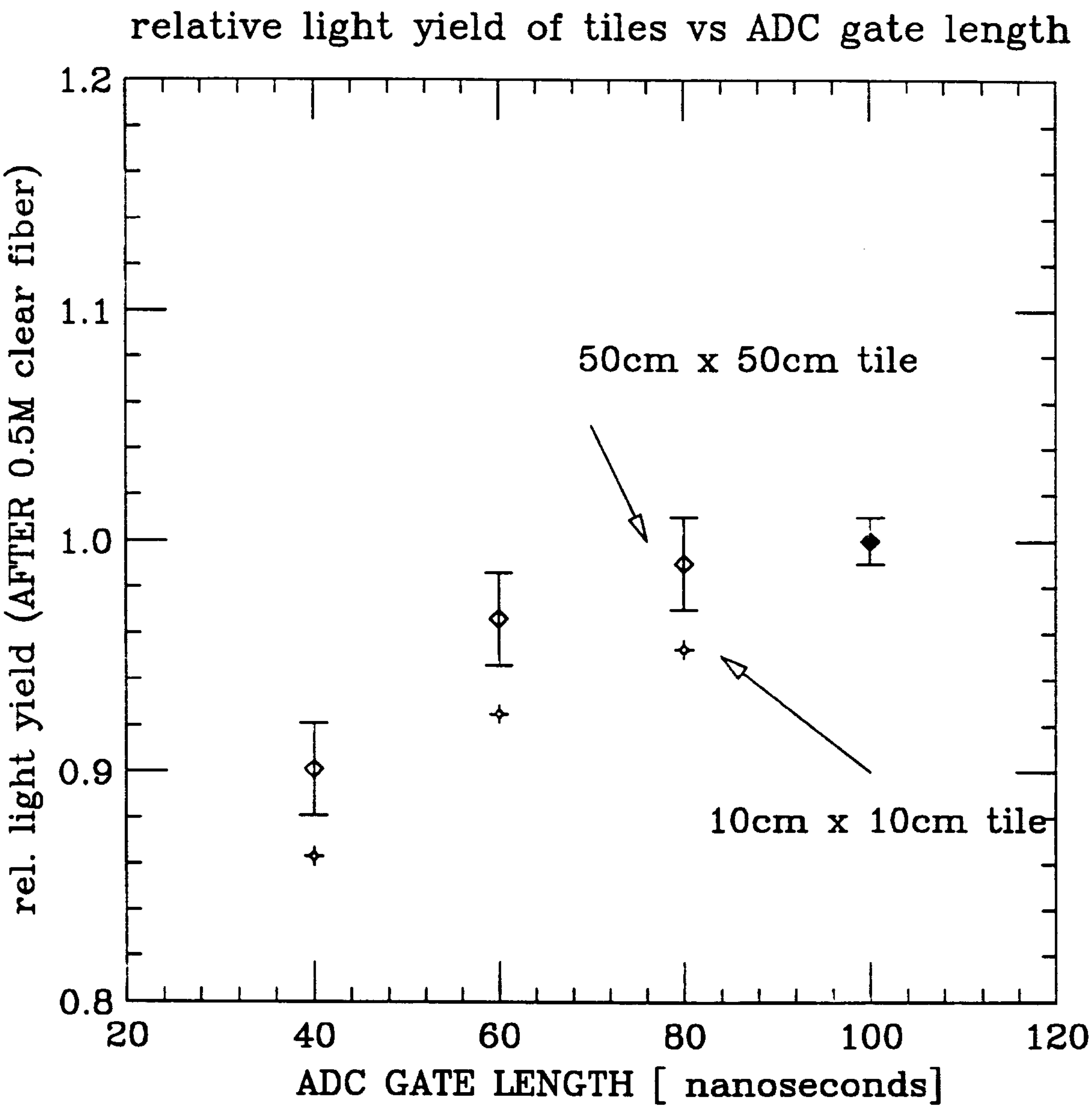


Figure 7: The relative response of the tiles vs the length of the integration time of the photomultiplier pulse height. The error bars represent the statistical uncertainty of the measurement. In this study we have used Hamamatsu PMT R580-17 and Le Croy ADC 2249A.