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RECENT R&D RESULTS ON TILE/FIBER CALORIMETRY

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ABSTRACT

We summarize the recent R&D results on the tile/fiber calorimetry. The issues discussed here address some of the action items from Calorimetry Optics Review during October '92 SDC Collaboration Meeting: study of the transverse uniformity of the response of the tiles as a function of fiber groove depth and the position of the fiber inside the groove; comparison of the light yield and the transverse uniformity of the response of megatiles vs individual tiles. We also present the results of the study of the light yield of tiles as a function of their size.

1 Experimental setup

The absolute light yield and uniformity of the response of tile/fiber assemblies was measured using a setup consisting of the collimated [1] Ru^{106} β source and a computer controlled x-y scanning table. The transverse size of the electron beam was $\approx$ 3 mm $\times$ 3 mm. The light collected by wave-length shifting (WLS) fiber imbedded inside the scintillating tile was transported via 3 m long clear fiber to a photomultiplier [1]. Clear fiber was connected to the PMT via an oil-coupler and a 3/4 inch $\times$ 3/4 inch $\times$ 2 inch lucite light mixer. The estimated variation in the coupling between the fibers and the PMT was less than 2%. The pulse from the PMT was integrated by a LeCroy 2249A ADC, triggered by a coincidence of the signals from two trigger counters located downstream of a tested tile. The length of the ADC gate was 80 nsec. Figure 1a shows an example of a pulse height distribution from a tile/fiber assembly. The absolute light yield of the tile/fiber assembly was determined from the ratio of the number of events with no measurable signal recorded in the ADC to the total number of triggers. The absolute light yield for this particular tile is 4.4 $\pm$ 0.1 photoelectrons per minimum ionizing particle (p.e. per mip). The dimensions and the pattern of the fiber groove for this tile are shown on Fig. 2. Figure 1b shows the ADC spectrum for a tile with light yield of $\approx$ 0.3 p.e. per mip, with one photoelectron peak approximately 30 ADC counts above the pedestal.

[1] We have used the Philips XP2081B PMT [3] with 'green-extended' photocathode.

2 Light yield vs fiber groove depth and the position of the fiber

We have studied the light yield and the uniformity of the response of tile/fiber assemblies as a function of the depth of the fiber groove. We have used 4mm thick, 10.8 cm $\times$ 10.8 cm SCSN-38 tiles, as shown on Fig. 2, and green WLS fiber BCF-91A [4], 0.83 mm diameter, spliced to 3 m of clear Kuraray fiber. The width of the fiber groove was 0.038 inches. We have studied the tiles with three different depths of fiber groove: 0.040 inches, 0.065 inches and 0.100 inches. Figure 3 shows the uniformity of the response of the tiles with different depths of the grooves. For the tile with 0.040 inch deep groove, the light yield in the fiber region is higher than the light yield in the central region of the tile; for the tile with 0.065 inches deep groove the light yield in the fiber region has approximately same value as in the central region, while for the tile with the groove depth of 0.100 inches, the light yield in the fiber region is on average lower that the light yield in the central region. Figure 4 shows the uniformity of the response of the tiles in the region $\pm$ 0.5 inches around the position of the fiber groove. Figure 5 presents the ratio of the light yield in the fiber region to the light yield in the central region of the tile as a function of the groove depth.

Table 1 shows the light yield and the uniformity of 4 mm thick tile/fiber assemblies. It indicates that the optimal uniformity of the response of the tile is achieved by choosing the groove depth of 0.065 inches ($\approx$ 1.6 mm). The r.m.s./mean of the uniformity of response is approximately 2%. It indicates that the average light yield of the 4 mm thick tiles increases very slowly (see Fig. 6) with depth of the groove, approximately 9% for variation in the groove depth between 0.040 inches to 0.100 inches. This increase is equivalent to a change of about 1.5% per 0.010 inches variation of the fiber groove depth.

We have studied the light yield and the transverse uniformity of the tiles as a function of the position of the fiber inside the groove. The 0.83 mm ($\approx$ 0.033 inches) diameter WLS fiber was forced to be on the top or on the bottom of the 0.065 inch and 0.100 inch deep grooves by inserting short clear fiber 'stubs' inside the fiber groove. Adequate care was taken to make sure that the WLS fiber was not forced above the surface of the scintillating tile. We have found that both the average light yield and the transverse uniformity of the response did not depend on the position of the fiber inside the groove.

3 Absolute light yield measurements of tile/fiber assemblies

Table 2 summarizes the comparison of the absolute light yields of tiles with different types of the WLS and the clear fibers. The tile used in the above comparison was built using

fiber groove depth	relative light yield	r.m.s./mean
0.040 inches	0.95 ± 0.02	3.1 %
0.065 inches,fiber on top	0.98 ± 0.02	1.9 %
0.065 inches,fiber on bottom	1.02 ± 0.02	1.9 %
0.100 inches,fiber on top	1.04 ± 0.02	3.0 %
0.100 inches,fiber on bottom	1.04 ± 0.02	3.0 %

Table 1: Summary of light yield and uniformity studies

WLS fiber	clear fiber	abs light yield
0.83 mm dia., Y11(250), strd clad	Kuraray, strd clad	2.1 ± 0.1
0.83 mm dia., Y11(250), multiclad	Kuraray, strd clad	2.4 ± 0.1
0.83 mm dia., Y11(250), multiclad	Kuraray, multiclad	4.4 ± 0.2
0.83 mm dia., BCF-91A(200), strd clad	Kuraray, multiclad	3.8 ± 0.1

Table 2: Summary of the absolute light yield studies. The numbers in the parentheses correspond to number of parts per million (ppm) by weight of a fluorescent dye in the fiber core.

4 mm thick SCSN-38 scintillator. The transverse dimensions of the tile were 10.8 cm × 10.8 cm, with the σ [2] fiber groove pattern. The diagram of the tile is shown on Fig. 2. The edges of tiles were painted with white reflective paint [4], and the tile was wrapped with aluminized mylar. The ends of WLS fibers were mirrored at the FNAL facility using the sputtering technique. Figure 7 shows the distribution of the ratio of the light yield of tiles read out by the fibers with and without mirrored ends. The sputtering of the ends of WLS fibers terminated inside the tile increases the light yield of tile/fiber assembly by about 40%, relative to the light yield of the tile with unmirrored WLS fiber. The WLS fibers were spliced to various types of 3 m long clear fibers. The highest light yield of tile was achieved for the combination of the WLS-multiclad/clear-multiclad fibers [8].

4 Single tiles vs megatile study

A megatile [5] is constructed by using white epoxy mixture [6] to glue several individual tiles together. The epoxy is used for both the structural support, and as a reflective surface at the edges of the tiles. The megatile technique of assembly of tiles from same calorimeter depth layers reduces significantly the number of individual elements to be handled during the construction of the calorimeter. The disadvantages of the megatile technique are an introduction of an additional step to the production of the calorimeter (filling the separation grooves with white paint/epoxy mixture) and increase in the cross-talk of the light between the neighbouring tiles.

We have compared the light yield and the uniformity of the response of single 10.8 cm × 10.8 cm, 4 mm thick (≈ 0.157 inches) tiles with a 2×2 megatile. The separation groove was 0.030 inches wide and 0.150 inches deep. The bottom portion (0.005 inches) of the separation groove was originally uncut. Figure 8 shows the scan of two tiles from the 2×2 megatile. The average light yield of a tile within the megatile was ≈ 5% lower than for identical single-cut tile. The uniformity of the tiles within the megatile, shown of Fig. 9 had r.m.s./mean of approximately 2%, excluding the crack region.

The average cross talk between neighbouring tiles within megatile was between 1% to 2% per edge of the tile. We have attempted to reduce the cross talk between neighbouring tiles be milling out the remaining 0.005 inches of scintillator from the separation groove and by applying the pressure on the megatile. We have also tested the tile-to-tile light cross-talk after filling the 0.005 inches of cut separation groove with white paint. However these techniques were not able to reduce the cross-talk between neighbouring tiles below 1% per single edge of the tile.

5 Fiber splicing

The green WLS fibers were spliced to clear fibers was using a technique [7] developed by the MSU group. The fibers were spliced by focusing the light from a 250 watt lamp on the fiber joint. The focus was achieved using an elliptical reflector with a gold coating to maximize the reflection of the light in the infrared wavelength range. The focus at the splice was approximately 1 cm wide. The fibers were jacketed by a Fluorinated Ethylene Propylene (FEP) shrink tubing which contracted, but did not melt during the heating process. The shrink tubing provided the mechanical protection for the splice, while still maintaining a high degree of flexibility.

The transmission of the light across green-to-green fiber splices was studied using a setup consisting of a UV lamp equipped with 400 nm long pass filter and a photodiode as a readout device. The current from photodiode was recorded as a function of the position of the UV lamp along the WLS fiber.

The transmission of the light across the green-to-green fiber (0.75 mm diameter, Y11(150) multiclad WLS fibers) splices was studied. Figure 10a shows a DC current from the photodiode as a function of a location of the UV lamp along the green WLS fiber. Figure 10b shows the DC current measurement for the same green WLS fiber, after the green-to-green fiber splice was introduced. The location of the splice is 130 cm away from the readout device.

Figure 10c shows the ratio of a DC current from the first and the second measurements, as a function of a location of the UV lamp along the fiber. The decrease in the ratio of the light yield between the spliced and the unspliced fiber corresponds to the transmission

of 91% of the light across the splice. Figure 11 shows a distribution of transmission across green-to-green fiber splices for a series of fibers. The average transmission was about 92% and the r.m.s./mean of the distribution was $\approx 3\%$.

In order to test the reproducibility of the green-to-clear fiber splices we have prepared two series of 35 fibers, 0.75 mm diameter, Y11(150), standard-clad and 0.75 mm diameter, Y11(150), multiclad fibers. One of the ends of the WLS fibers was pained black, the other end was spliced to 2.5 m long, 0.75 mm diameter clear Kuraray fibers [8]. The standard clad WLS fibers were spliced to the clear fibers with standard cladding and the multiclad WLS fibers were spliced to the multiclad clear fibers.

Figure 12 shows the distribution of relative light yield of the two series of fibers. It indicates that for both the standard clad and the multiclad clear fibers, the r.m.s./mean of splices was about 4%. The light yield of the tiles read out with the 0.75 mm diameter green multiclad WLS fibers spliced to clear multiclad fibers, was higher by a factor of ≈ 1.4 relative to the light yield of the tiles read out with the standard clad WLS fibers spliced to standard clad clear fibers. Similar studies of light transmission for standard clad and multiclad 0.83 mm diameter fibers are presently underway.

6 Attenuation of light in green WLS fiber

We have studied the attenuation of the light in green WLS fibers. The measurement was done by exciting the tile/fiber assembly using a Cs^{137} γ source and recording the DC current from a PMT coupled to the fiber. In this measurement we have used 3 m long green WLS fiber BCF-91A, standard cladded, 0.75 mm diameter, spliced to 1.5 m clear Kuraray fiber. The unspliced end of the green fiber was painted black to eliminate the possibility of the light reflection. During each measurement, the length of the green WLS fiber inside the tile was kept constant, however the distance between the green-to-clear fiber splice and the tile edge was varied.

Figure 13 shows of the relative light yield of the tile as a function of the distance between the edge of the tile and the green-to-clear fiber splice. The measurements were done with the WLS fiber inserted to the tiles with two different types of the groove pattern. Square symbols correspond to the measurement done with the straight groove tile and circle symbols to the measurement done with the WLS fiber inserted to the tile with the σ groove pattern.

The attenuation length of the light in the green WLS fiber inserted to the straight groove tile was shorter than in case of the green fiber inserted to the σ groove tile. Using the two-exponential function, the attenuation function of the light from the σ groove tile could be described as:

$$f(L) = 0.2 * exp(-L/20\ cm) + 0.8 * exp(-L/240\ cm) \quad (1)$$

7 Light yield of tiles as a function of their size

In case of detectors with the projective geometry, the tiles forming the front (inner) layers of a calorimeter will be smaller than the tiles forming the the back (outer) layers of the calorimeter. For example the ratio of the size of inner-to-outer layers of HAC1 tiles in the SDC barrel calorimeter [9] is approximately equal to 1:2.

Since the variation in the light yield of the tiles forming a single readout tower would lead to the additional constant term in the energy resolution of the calorimeter [10]- [11], it is important to understand the variation in the light yield of the tile/fiber assemblies as a function of the size of the tiles and the pattern of the fiber groove.

We have measured the light yield of a group of the tiles, with their transverse sizes ranging from 10.8 cm×10.8 cm to approximately 30 cm×30 cm, with the σ pattern of the location of the readout fiber. The measurements were done using a 0.75 mm diameter, 90 cm long WLS green fiber BC-91A, spliced to 3 m long standard clad clear Kuraray fiber. The light yield of the tiles with shorter length of the readout fiber groove was corrected for the attenuation of the light in the green WLS fiber using the equation 1.

Figure 14 shows the relative light yield of the tiles, as a function of the parameter l/A, where l corresponds to the length of the green fiber imbedded inside the tile and A corresponds to the area of the tile. The plot indicates that the relative light yield of the tiles scales approximately with the parameter l/A.

Using the above parametrization, the predicted ratio of the light yield of the front layer tiles to the back layer tiles for the SDC barrel HAC1 calorimeter in the central η region would be:

$$ratio(front/back) = \frac{(l/A)_{front}}{(l/A)_{back}} = 1.4 \quad (2)$$

It should be noted that the above factor of 1.4 does not include the correction due to different lengths of clear fibers used in routing of light between the scintillating tiles and the PMTs. In case of the SDC HAC1 calorimeter this difference would be approximately equal to 1 m. Taking the attenuation length of a clear fiber to be λ^{clear} =7.8 m [2], the ratio of the light yield

[2]The attenuation length of standard clad, 0.83 mm diameter, clear fiber from Kuraray

of front layer tiles to back layer tiles for the SDC barrel HAC1 calorimeter in the central η region corrected for the different length of clear fiber would be:

$$ratio(front/back)^{corr} = ratio(front/back) \times e^{-1/7.8} = 1.4 \times 0.88 = 1.23 \quad (3)$$

The scaling of the light yield of tile/fiber assemblies with parameter l/A indicates that the response of the of the tiles within same readout tower can be adjusted by varying the length of the WLS fiber groove inside the tile. This adjustment can be achieved in case of the σ fiber pattern groove by increasing or decreasing the distance between the location of the fiber groove and the edge of the tile. The above technique of the uniformization of the light yield of the tiles within same readout tower is presently studied for the CDF End Plug Upgrade project [5].

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] D. Underwood et al., to be published.

[2] P. de Barbaro et al., Nucl. Instr. and Meth. A315 (1992) 317

[3] Philips XP2081B photomultiplier, 1990 Photomultiplier Data Book, PC04, Philips Components.

[4] Green WLS fiber BCF-91A from Bicron Inc., 12345 Kinsman Rd., Newbury OH 44065-9677.
White reflective paint, BC-620 from Bicron Inc.

[5] CDF End Plug Calorimeter Upgrade Design Report, July 1992.

[6] The white paint/epoxy mixture was prepared by milling TiO_2 with the epoxy resin (DER332 by Dow Chemicals) in 1:2 weight ratio. Then white paint/epoxy mixture was combined with the hardener (Jeffamine (TM) Polyoxypropyleneamines D-230 by Texaco): for 100 g of white paint/epoxy mixture we add 21.3 g of D-230 hardener.

[7] J. Huston et al., in preparation.

[8] Standard clad and multiclad fibers Y11 from Kuraray International, 200 Park Ave., New York, NY 10166. The index of refraction of the fiber core, n_1, is 1.59. The index of refraction of the cladding in standard fibers, n_2(strd clad) is 1.49, while for the multiclad fibers the outer cladding has the index of refraction, n_2(multiclad) equal to 1.41. The use of a cladding material with lower index of refraction increases the trapping efficiency of a multiclad fiber relative to a standard clad fiber by a factor of approximately 1.80:

$$Tef(strd\ clad) = (1 - cos(n_2(strd\ clad)/n_1))/2 = 3.14\% \quad (4)$$

$$Tef(multiclad) = (1 - cos(n_2(multiclad)/n_1))/2 = 5.67\% \quad (5)$$

[9] M. Banas, private communication.

[10] A. Beretvas, J. Freeman, Monte Carlo Investigation of Light Yield Uniformity, SSC-SDC-F-100 Note.

[11] 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.

Figures

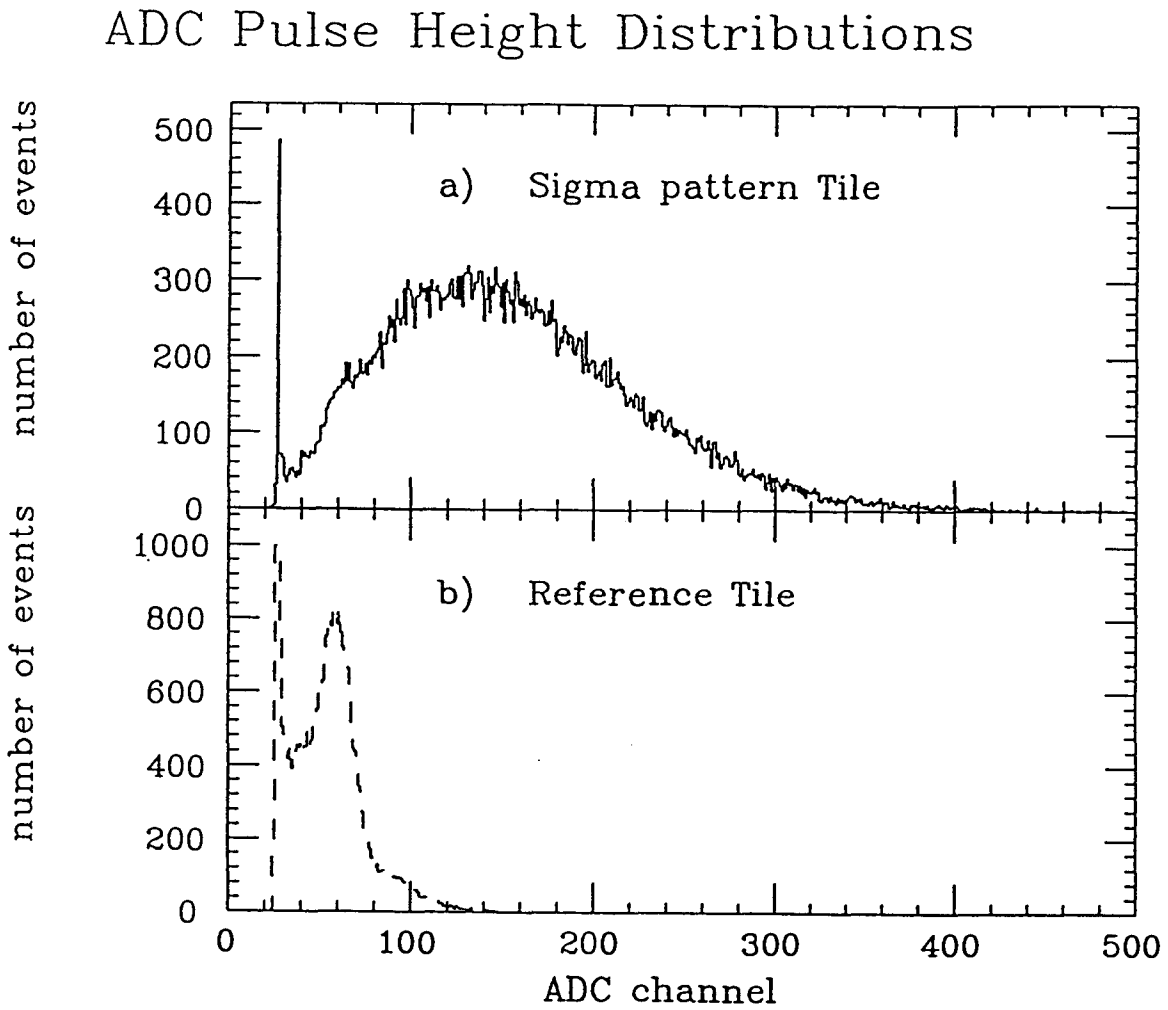

Fig.1: ADC pulse height spectrum for tiles using electrons from collimated β source:
a) ADC spectrum for the σ tile built using 4mm thick SCSN-38 scintillator. The transverse size of the tile is 10.8 cm $\times$ 10.8 cm (see Fig 2). The edges of the tile were painted with white reflective paint BC-620 from Bicron. Light was collected using 0.83 mm diameter Y11(250) multiclad WLS fiber from Kuraray, spliced to 3 m of multiclad clear Kuraray fiber. One of the ends of the WLS fiber was terminated inside the tile and was mirrored using the sputtering technique. The fraction of triggers with no ADC deposition is equal to 1.20 $\pm$ 0.05 % corresponding to the average light yield of 4.4 $\pm$ 0.1 photoelectrons (p.e.) per minimum ionizing particle (mip).
b) ADC spectrum for the reference tile. The light yield of this tile is $\approx$ 0.3 PE/m.i.p. The pedestal events are suppressed on Fig. 1b. The position of the one-photoelectron peak was used to calibrate the phototube and determine the number of ADC counts per 1 p.e. One photoelectron peak corresponded approximately to 30 ADC counts above the pedestal.

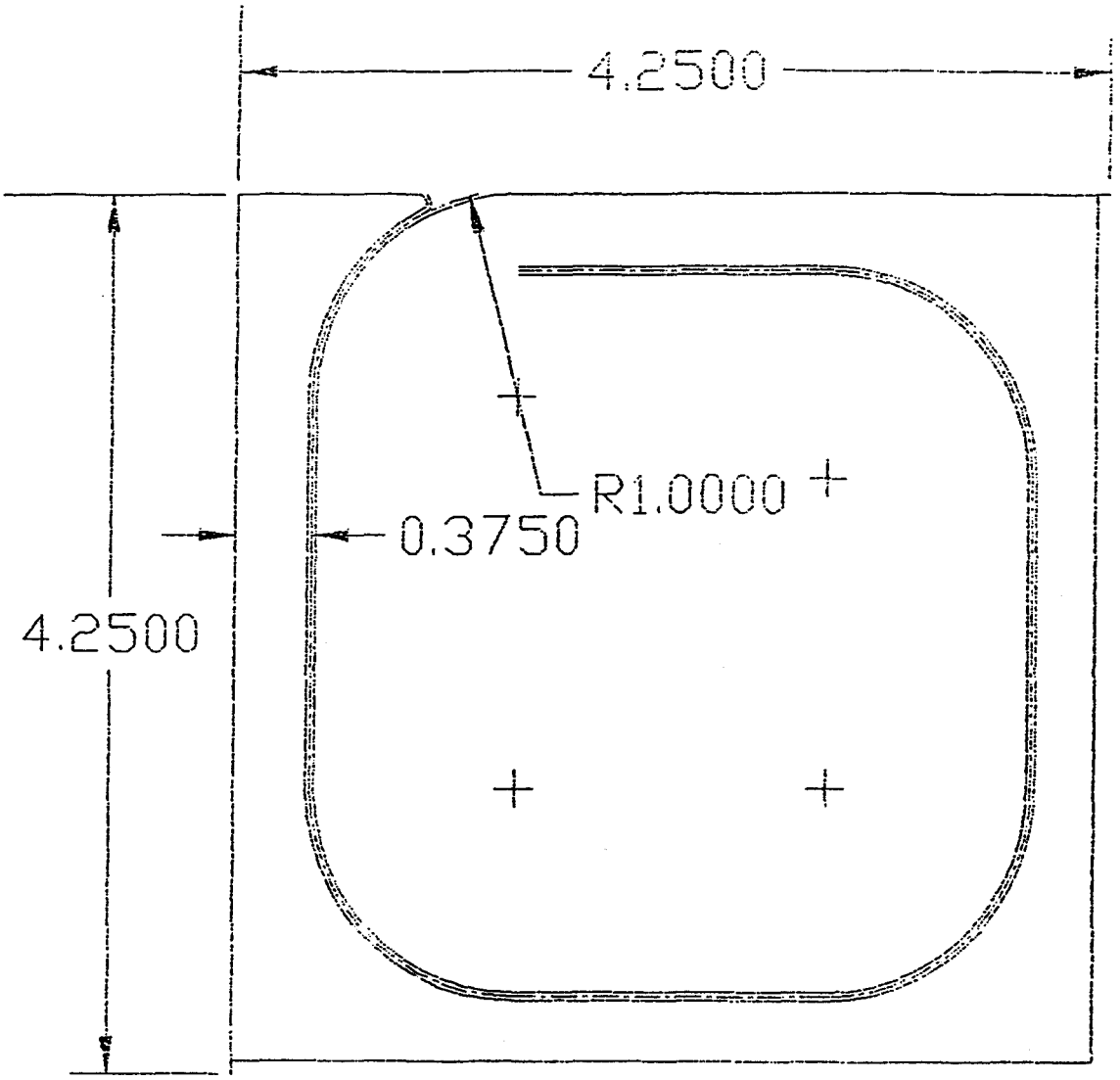

Fig.2: The diagram of the tile with the σ fiber pattern groove. The dimensions of the tile are expressed in inches. The ADC spectrum from this tile is shown of Fig. 1a.

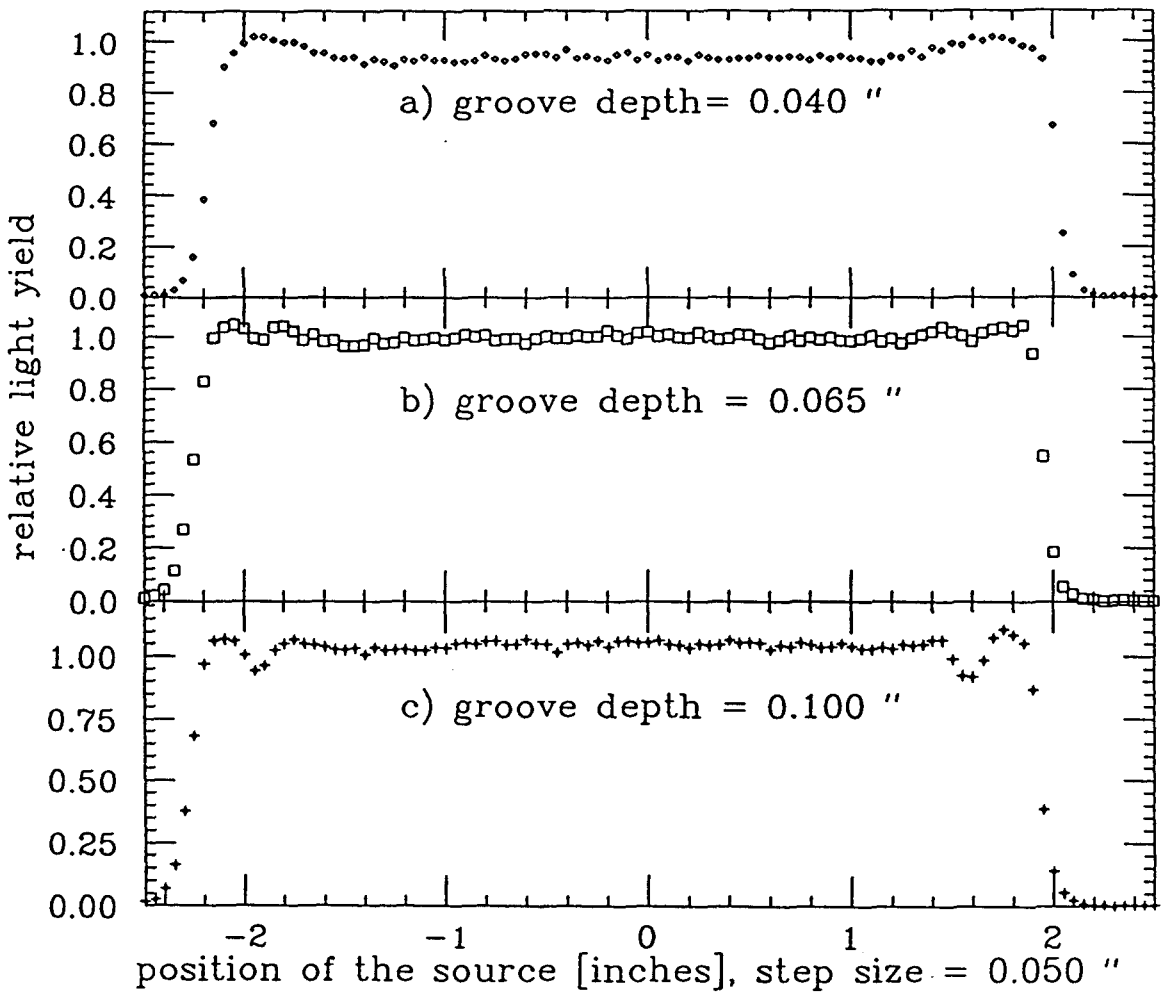

Fig.3: Transverse scan of 4 mm thick tile with different depth of fiber groove: a) 0.040 inches deep; b) 0.065 inches deep; c) 0.100 inches deep. The light yield of the tile relative to the average light yield of the tile with 0.065 inches deep groove is plotted as a function of the position of the electron source. The width of the groove is equal to 0.038 inches. The transverse dimensions of the tile were 10.8 cm × 10.8 cm (see Fig 2). The diameter of WLS fiber used was 0.83 mm.

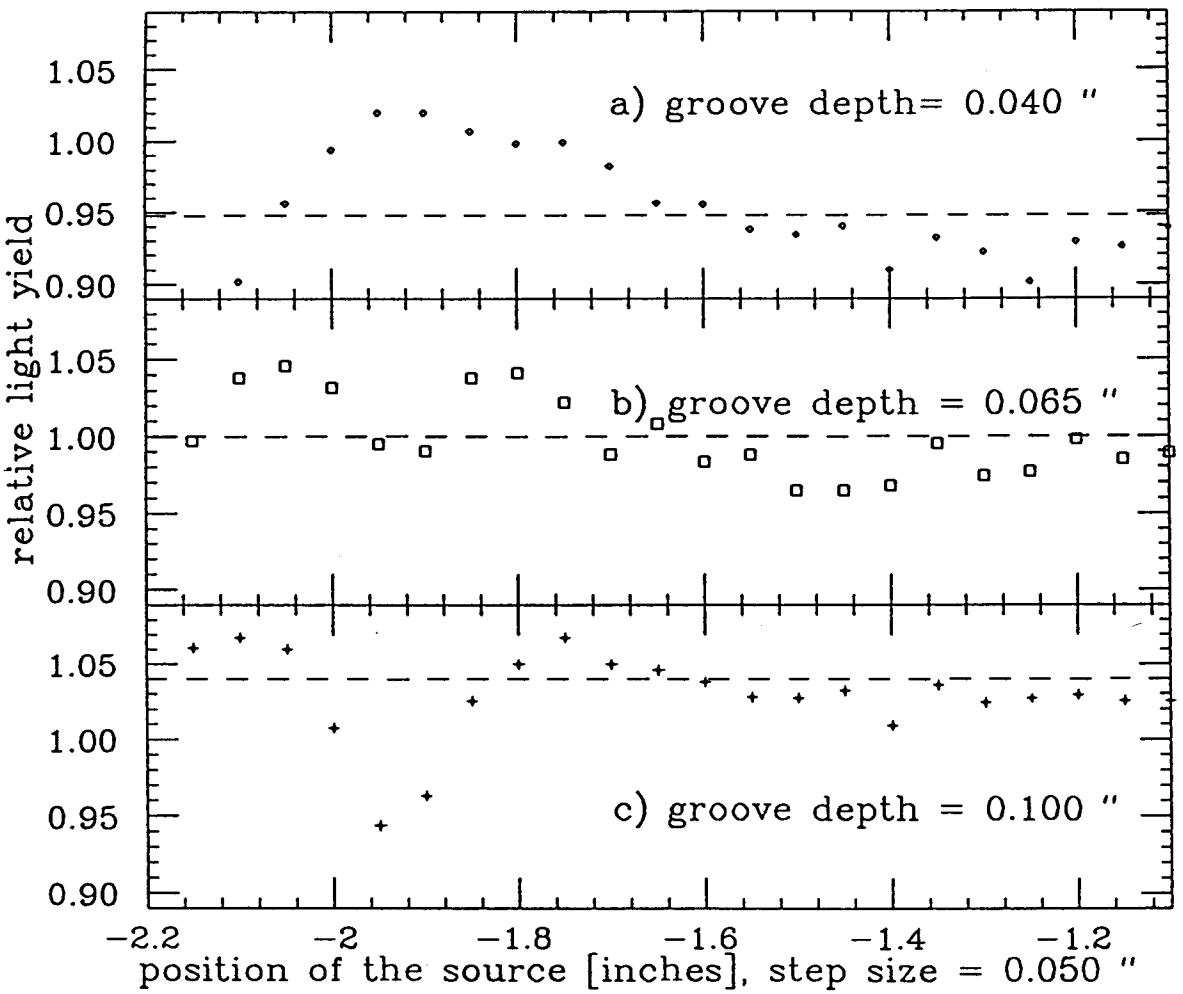

Fig.4: Transverse scan of 4 mm thick tile with different depth of fiber groove: a) 0.040 inches deep; b) 0.065 inches deep; c) 0.100 inches deep. Only the region ± 0.5 inches around the fiber position is shown. The horizontal line indicates the average light yield of the tile relative to the average light yield of the tile with 0.065 inches deep groove.

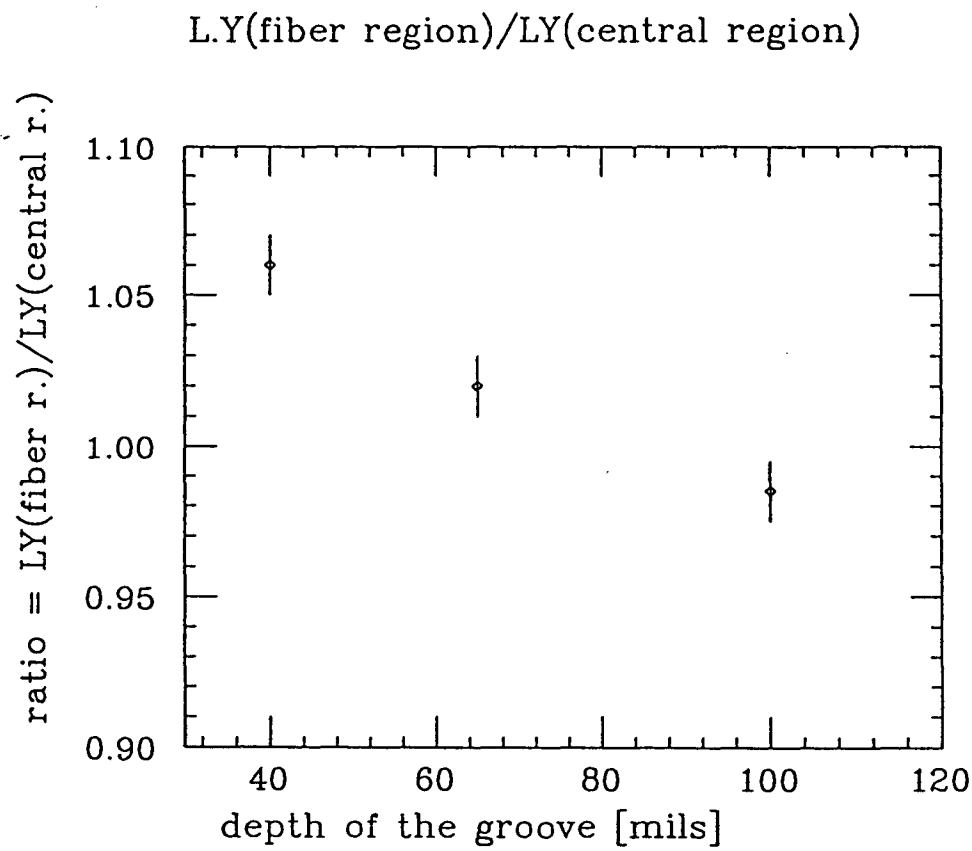

Fig.5: The ratio of the light yield of the σ tile in the fiber region, ($\pm$ 0.5 inches around the fiber position) to the light yield in the central region of the tile as a function of the depth of the fiber groove.

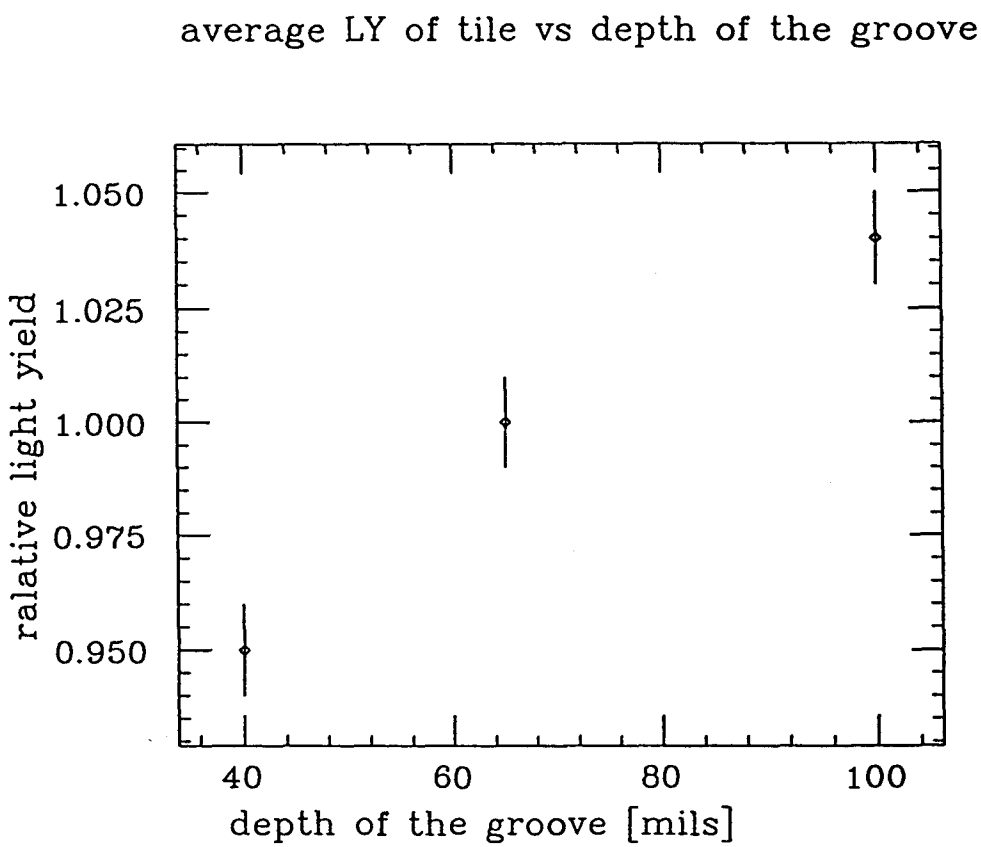

Fig.6: The average light yield of the σ tile as a function of the depth of the fiber groove. The slope corresponds to the increase of $\approx$ 1.5% per variation in the depth of the groove of 0.010 inches.

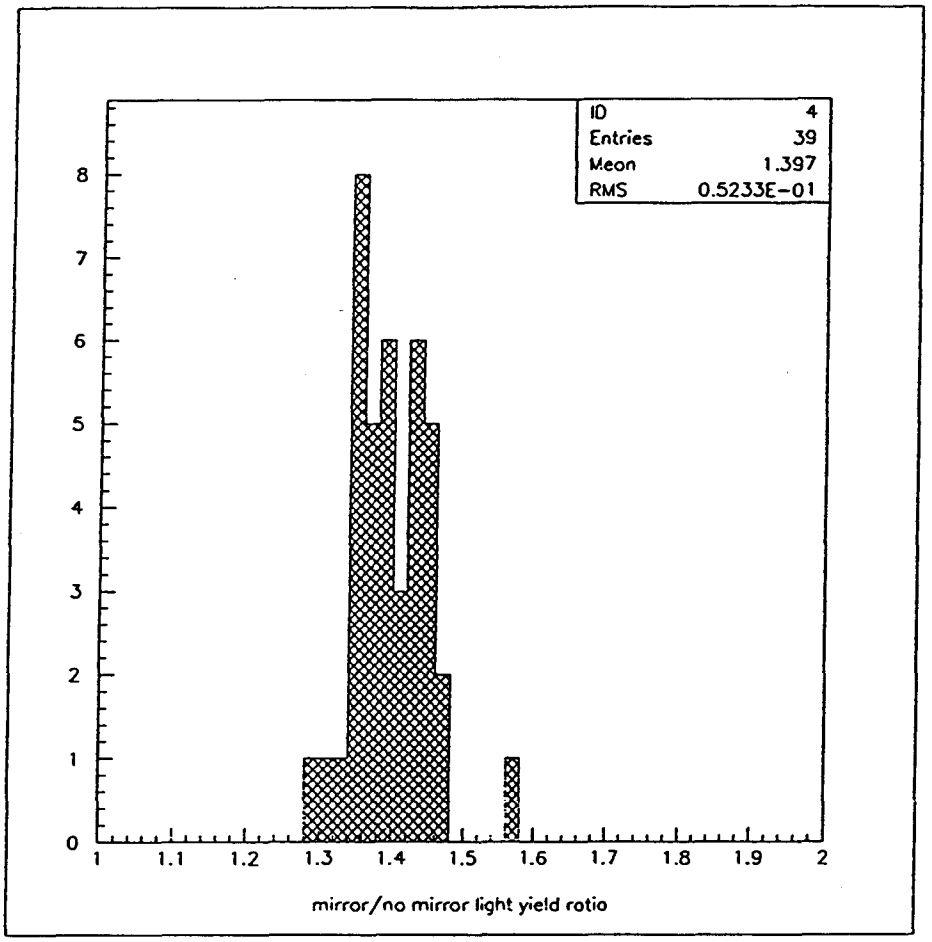

Fig.7: The distribution of the light yield of tile/fiber assemblies with the ends of the WLS fibers mirrored relative to the light yield of the tile/fiber assemblies after the mirroring was removed from the ends of the WLS fibers. The measurement was performed using a 4 mm thick SCSN-38 tile with the σ groove pattern (see Fig. 2). The mirroring was removed from the fiber ends using a sharp razor blade. The ratio was measured for a sample of control fibers during the mirroring of over 1200 fibers during a period of 3 weeks. The average ratio is equal to 1.40 with r.m.s./mean of the distribution below 4%.

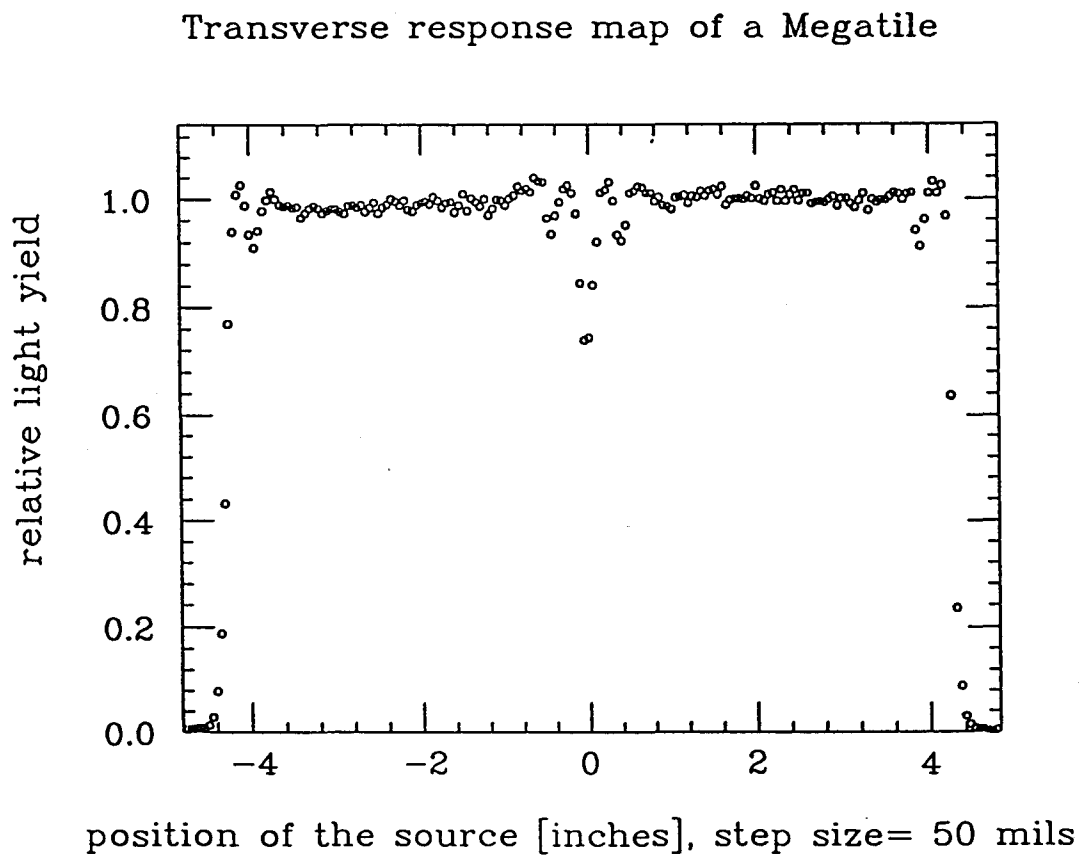

Fig.8: The transverse uniformity of the two σ tiles from the 2×2 megatile. The depth of the fiber groove was 0.065 inches and the separation groove between the tiles was 0.030 inches ($\approx$ 0.76 mm) wide. The relative light yield of the megatile is plotted as a function of the position of the electron source.

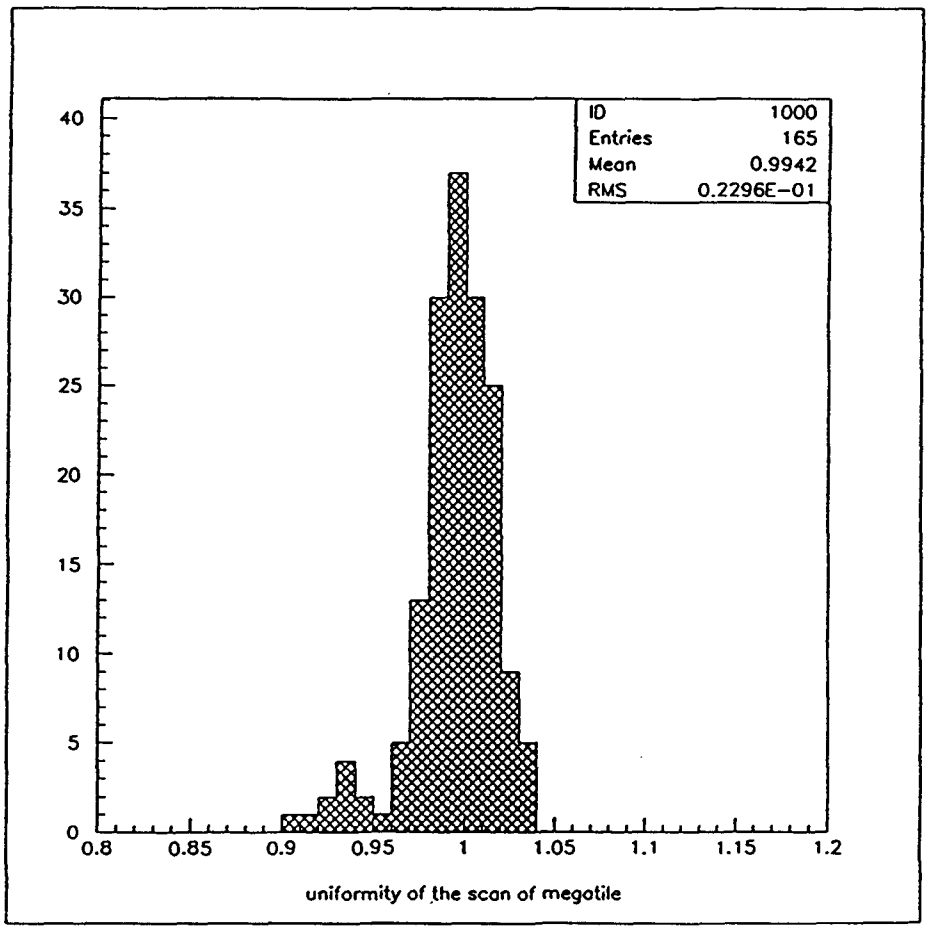

Fig.9: The distribution of the light yield of the megatile, normalized to the average light yield of the 2 × 2 megatile. The data corresponds to the scan from Fig. 8, excluding the points at the edges of the tile and the crack region between the tiles.

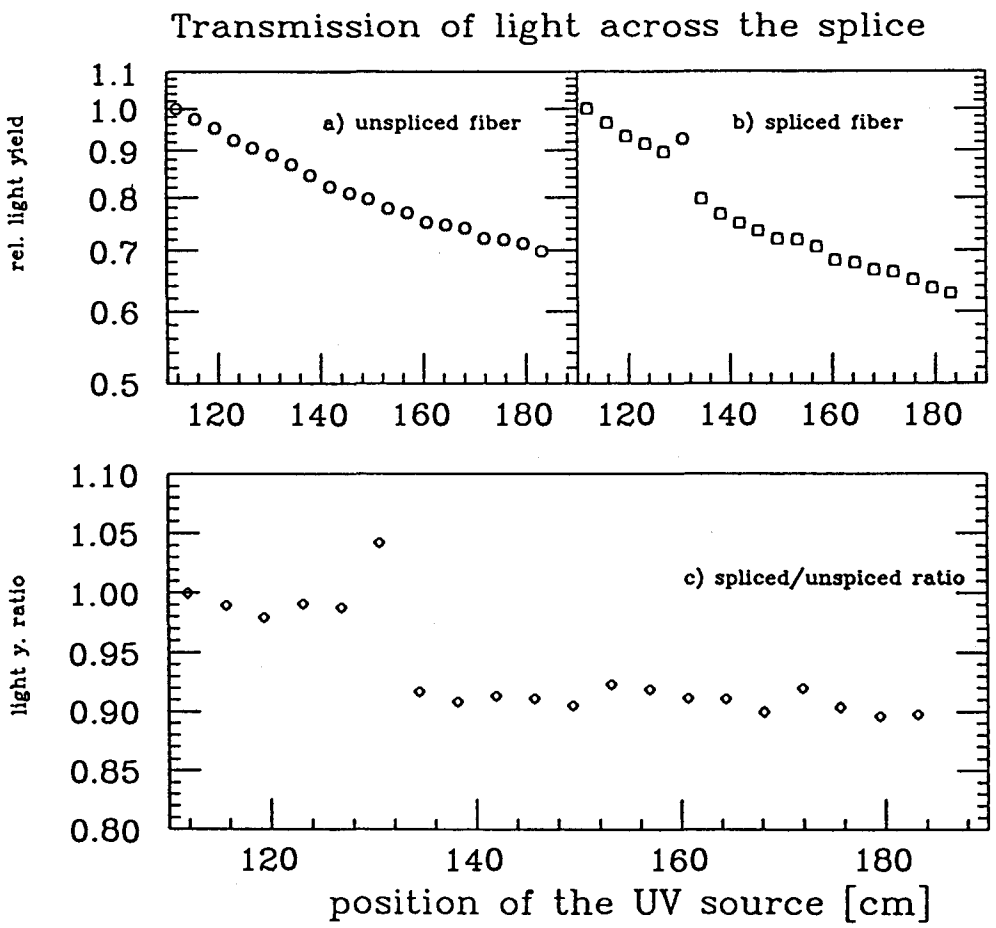

Fig.10: Transmission of light across a green-to-green fiber splice:
a) Relative light yield vs location of the UV source for a unspliced green WLS fiber;
b) Relative light yield vs location of the UV source for the same WLS fiber cut and respliced;
c) ratio of the two above measurements as a function of the location of the UV source. The decrease in the ratio of the light yield between the spliced and unspliced fiber corresponds to the transmission of 91% of the light across the splice. The local increase in the light yield ratio corresponding the position of the UV source at the location of the splice is caused by the fluorescence of the FEP shrink tubing.

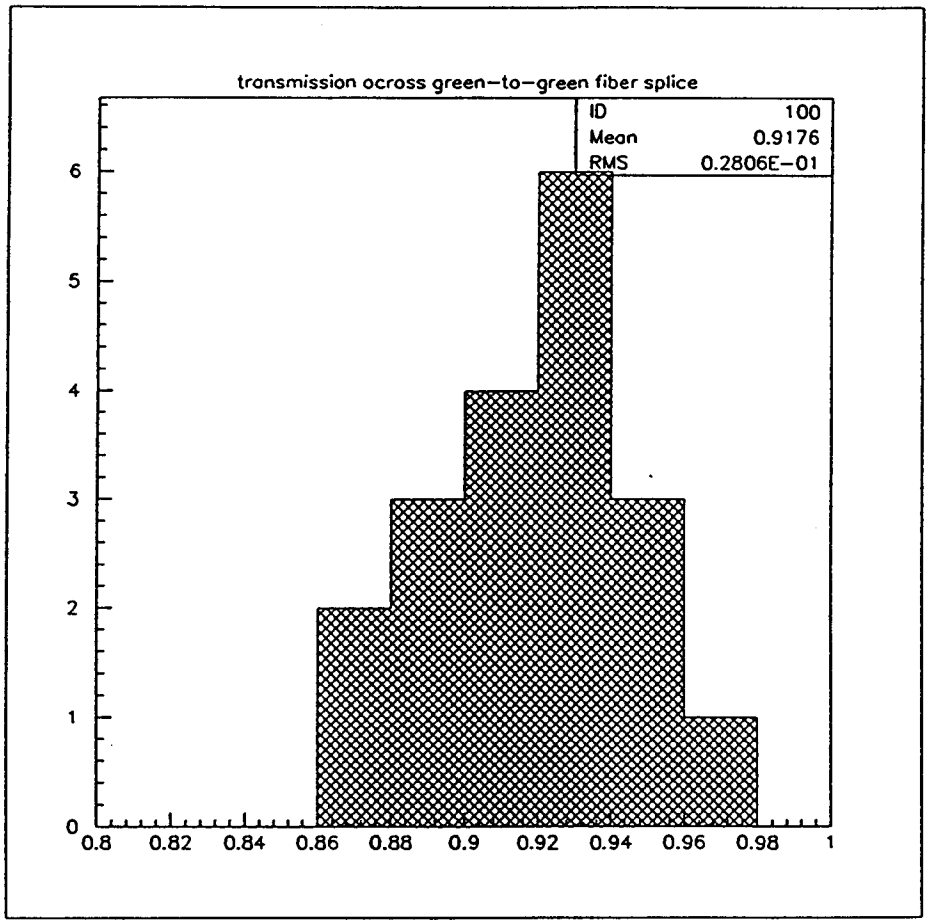

Fig.11: Distribution of transmission of light across green-to-green fiber splices measured for a series of Y11(150) 0.75 mm multiclad fibers from Kuraray.

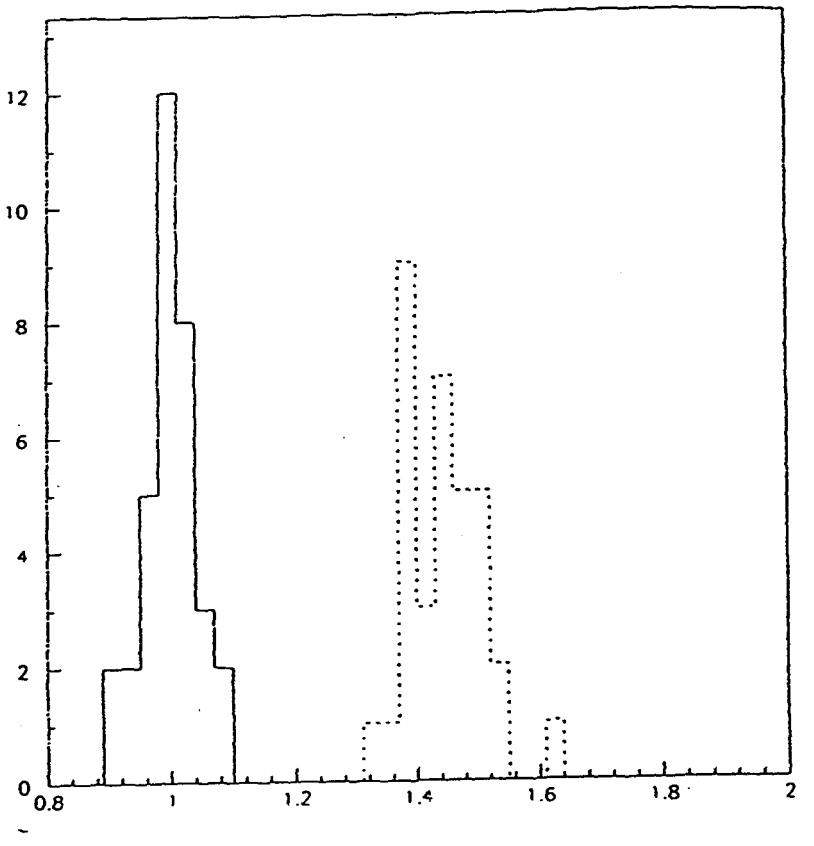

Fig.12: Distribution of relative light yield of two sets of 0.75 mm dia. spliced fibers. The distributions are normalized to the average light yield of standard clad WLS fibers spliced to standard clad clear fibers (histogram with solid line). The multiclad WLS fibers spliced to multiclad clear fibers (dashed line histogram) have light yield higher by factor 1.4. The r.m.s./mean of both distributions is approximately 4%.

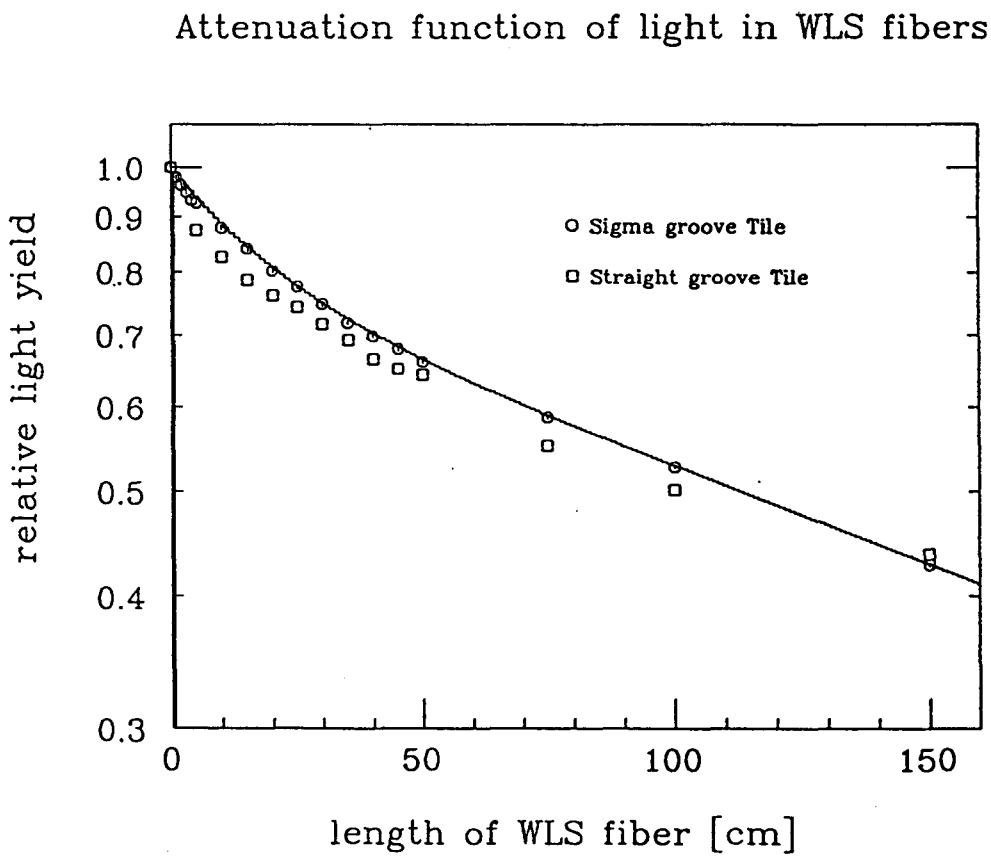

Fig.13: Attenuation function of light in the green WLS fiber, 0.75 mm diameter, standard clad, BCF-91A. The fiber was inserted to a tile with straight groove pattern (square symbols) and to a tile with the σ pattern groove (circle symbols). The line corresponds to the two-exponential fit, as described in the text.

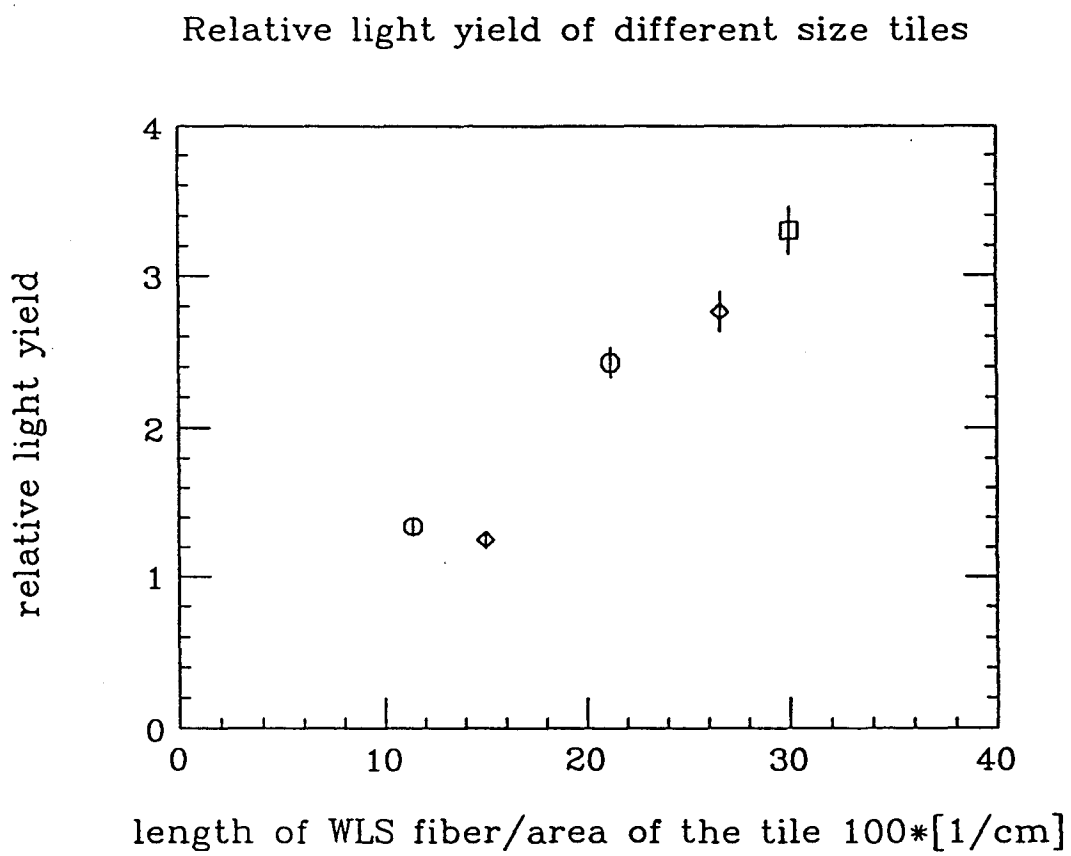

Fig.14: Light yield of various tiles plotted as a function of a parameter l/A, where l corresponds to the length of the WLS fiber inside the tile, and A corresponds to the area of the tile. Different tiles in the same projective tower are represented by the same symbol. From geometric considerations one expects that the average light yield of a tile would scale with variable l/A.