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A Scintillating Tile/Fiber System for High Energy Calorimeter with High Light Yield and Uniform Longitudinal and Transverse Responses

T. Asakawa, I. Fujiwara, S. Kim, K. Kondo, T. Mogami,
S. Munakata, H. Sato and H. Toyoda

Institute of Physics, University of Tsukuba

Abstract

We have performed R&D for a tile/fiber calorimeter system. Using a multi-turn wave length shifting (WLS) fiber, the response of tile/fiber system was made uniform to within 2.5 % over a tile. The response uniformity with respect to the tile size, which varies from 80 to 200 mm square, was controlled to within 3% (r.m.s.) by changing the WLS fiber length. Using HAMAMATSU R329 photomultiplier tube, the average light yield is larger than 2.5 photoelectrons per minimum ionizing particle.

1 Introduction

High energy experiments require a calorimeter with a fast response, a good signal-to-noise ratio, a good energy resolution, a small dead space and an easy maintenance. A system consisting of a tile-shaped scintillator with an embedded wavelength shifting (WLS) fiber for readout is designed to fulfill these requirements. Calorimeters composed of layers of various sizes of tile/fiber and iron or lead absorber plates are being developed for the Collider Detector at Fermilab (CDF) [1] and the Solenoidal Detector Collaboration (SDC) [2]. Scintillation lights produced in scintillator plates are converted to a longer wavelength by a WLS fiber embedded in a tile. The WLS fiber couples to a clear fiber and it then transmits the light to a photomultiplier tube (PMT). One of the issues of the tile/fiber system has been a non-uniform response in a calorimeter tower both longitudinally and laterally. The coil type fiber and tile system, proposed by the authors and shown in Figure 1, is expected to achieve good light collection and a uniform response. The coil structure allows to control light yield by changing the fiber length. This feature enables us to make uniform the light outputs out of tiles with different sizes in a calorimeter tower. As a tile is thinner at the fiber groove the response is smaller there and needs compensation. We have developed a way of the compensation. In this note we report R&D efforts for a tile/fiber system using 6 mm thick SCSN81 [3] scintillator and Y7 [4] wavelength shifter with a diameter of 1 mm, both manufactured by KURARAY.

2 The Principle of the Light Yield Measurement

2.1 Experimental setup

We evaluate the light yield in terms of the number of photoelectrons seen with a photomultiplier tube (PMT). The experimental setup for this measurement is shown in Figure 2. We excite a scintillator tile with a ^{90}Sr β-ray source. The source has a collimator of 5 mm in diameter. A trigger scintillator, 2 mm in diameter, is placed beneath the tile. The WLS fiber is coupled to the PMT with an air contact. We have used two types of phototubes, HAMAMATSU R329[1] and R464[2]. The signal is digitized using a LeCroy 2249A CAMAC ADC module, and then read out with an NEC PC-9801 personal computer.

2.2 Definition of light yield

An average number of photoelectrons is calculated using a PMT pulse height distribution with typically 3000 events. The pulse height distribution is a smeared Poisson distribution. The average number of photoelectrons can be determined from the pulse height distribution once we know the pulse height for a single photoelectron.

[1]The R329 photomultiplier tube has the same type of photocathode as R580, which is used for the CDF central electromagnetic calorimeter, but has more dynode stages and thus a higher gain.

[2]The R464 is a so-called "quantacon" PMT which has a good separation for one and two photoelectrons. But it has a lower quantum efficiency and shows a somewhat non-linear response for a large pulse height.

The pulse height for a single photoelectron is measured with the same experimental setup (Figure 2) by sufficiently reducing the light intensity by an insertion of a neutral density filter (with a typical transmission of 2 %) between the WLS fiber and the PMT. Figure 3 shows a typical pulse height distribution for this measurement. The peak at about 43 ADC counts corresponds to a single photoelectron. Contribution from events with two or more photoelectrons is negligible. In order to determine the peak position precisely, we fit the distribution near the peak with a single Gaussian distribution. The fitted distribution is shown in the Figure as a curve.

The next step is to determine the average number of photoelectrons given a pulse height distribution and a single photoelectron peak position. A typical pulse height distribution is shown in Figure 4. First, we scale the x-axis in units of the single photoelectron peak. We tried two different methods for the determination. First method uses the average value of a pulse height distribution. The second method fits a distribution with a smeared Poisson distribution where the position and the width of a single photoelectron peak are fixed to the previous measurement (Figure 3). The fitted curve for the pulse height distribution is also shown in Figure 4. The results from the two methods agree well: The difference is usually smaller than the statistical precision of the measurements. In the remainder of this paper, we use the first method for the determination.

3 Light Yields vs. the Fiber Length and the Tile Size

In this section, we discuss the light yields when the length of a WLS fiber and the size of a tile are changed. A tower of a calorimeter with a projective tower geometry covers a certain solid angle with respect to a nominal collision point. This means that scintillator tiles within a tower have different physical sizes at different depths in a tower. We wish to obtain constant light yields out of different layers for a better energy measurement. As we shall see soon, the light yield out of a tile varies considerably with its size. We propose a method to achieve a more constant light yield by changing the length of a WLS fiber embedded in a tile.

3.1 Light yield vs. the fiber length

We discuss the light yield of a tile/fiber system as a function of the length of a WLS fiber embedded in a tile. We also changed the concentration of the wavelength shifter Y7 in the range from 10 to 400 ppm. A tile is 120 mm by 160 mm and 6 mm thick. The groove shape in the tile is a circle with an radius of 57 mm, and the groove depths are 1, 2, 3 and 4mm corresponding to the number of turns of fiber embedded in a tile. In a tile with a given size, we embedded 1, 2, 3 and 4 turns of WLS fiber. A HAMAMATSU R464 photomultiplier tube is used for this measurement. All measurements in this section are on the center of tiles. Figure 5 shows the light yield as a function of the length of a WLS fiber. Points along x-axis corresponds to 1/2, 1, 2, 3 and 4 turns of WLS fibers. A longer fiber with more turns means that lights emitted by a scintillator tile have more chance to encounter the WLS material while traveling in the tile. Thus we expect that a longer fiber can collect more light. This is the case with a fiber with a lower Y7 concentration, as seen in the figure. For a higher concentration of WLS, the light yield starts to saturate. For a further higher concentration, the light yield decreases with the fiber length. The light attenuation in WLS fibers seems to be the cause of the saturation and the decrease.

3.2 Light yield vs. tile size

Light yields from tiles with different sizes are measured with an R329 PMT. Tiles are 80, 120, 160, 200, and 250 mm square and 6 mm thick. The groove shapes of their tiles are circles, and those diameters are 3 mm shorter than their side lengthes. The concentration of a WLS fiber is fixed to 30 ppm. All fibers embedded in tiles are 4 turns. The lengths of them are 955 mm for the 80mm sqaure tile, 1457 mm for 120 mm, 1959 mm for 160 mm, 2462 mm for 200 mm, and 3090 mm for 250 mm. It has turned out that smaller tiles give more light yield, as shown in Figure 6. The light attenuation in a tile seems to be the cause of the decrease in the light yield with the increasing tile size.

3.3 Responses of tiles with different sizes

A way of obtaining a constant light yield for tiles with different sizes is to change the length of a WLS fiber within a tile according to the tile size. An alternative is to change the wavelength shifter concentration according to the tile size. It is difficult to control light yields out of tile/fibers of various sizes by this way, so we have tried the first way.

Sample tiles are 80, 120, 160, and 200 mm square and 6 mm thick. The concentration of Y7 in a fiber is fixed to 30 ppm. The PMT used in this measurement is R329. The fiber length for a tile with a given size is chosen using Figure 7. The numbers of turns of a WLS fiber are 1.08 for the 80 mm square tile, 1.46 for the 120 mm, 2.10 for the 160 mm, and 4.00 for the 200 mm. We have decided them so that light yields for all size tiles should be identical to that for the 200 mm square tile with a 4-turn fiber. Figure 8 demonstrates that the light yields of tiles with different sizes are made uniform to within 3% with this method. The average light yield is about 2.6 photoelectrons. We can expect to get more light yield for less than 200 mm square tiles.

4 Transverse Response Uniformity

In this section we discuss the transverse uniformity of the light yield within a tile. A tile/fiber system contains singular points within a tile, namely the groove where a WLS fiber is routed. Also the existence of the groove may produce a difference in the optics between the regions inside and outside the groove. Also, the light attenuation in a tile would generally introduce the non-uniformity. Therefore it is important to demonstrate that the tile/fiber system can achieve a good transverse uniformity. We need the transverse uniformity to be less than 2.5%.

sample	light yield (# photoelectrons)	response uniformity (R.M.S. [%])
A	2.59 ± 0.08	2.57 ± 0.15
B	3.06 ± 0.10	2.39 ± 0.14

Table 1: Effect of painting the tile surfaces white.

4.1 Experimental setup

We measured responses of tile/fibers using a ^{90}Sr β-ray source. We made an automatic scanning system that positions a source with an accuracy of better than 50 μm. The experimental setup for this measurement is shown in Figure 9. In this setup, the source and a trigger counter are fixed on the table, and a sample tiles moves two-dimensionally with respect to them. The trigger counter under a sample tile consists of a scintillator, a light guide and a PMT. The scintillator is 2 mm in diameter. Since the β-ray source is disk shaped with an active region of about 1 cm in diameter, we use a lead collimator with 5 mm diameter. The PMT used in this measurement is R329. We measured responses at 100 points which distribute uniformly on a tile. The r.m.s. variation of the 100 responses is used as a measure of the transverse uniformity.

4.2 Effect of reflection on surfaces of a tile

Samples A and B consist of a 120 mm square tile with a 2-turn WLS fiber. The groove shape is a circle and its depth is 2 mm. The four side surfaces of sample B are painted with Bicron white paint BC-650 (BWP). And both samples are wrapped in aluminized mylar. Figures 10 and 11 show response maps for them. We normalize the pulse heights with an average pulse height of 100 points, and the average pulse height is fixed to 100. The pulse height is smaller for sample A outside the coil than inside. Sample B is more uniform than sample A. Diffuse reflections by white paint at the sides seem to have improved the light collection by the WLS fiber. Sample B showed the larger light yield and the better response uniformity than sample A. Table 1 summarizes the average and r.m.s. variation of the responses.

4.3 Effect of polishing the groove

We measured the effect of polishing the fiber groove on the response uniformity using the following two types of samples. One has the polished fiber groove and the other has unpolished one. Both tiles are 120 mm square and 6 mm thick and their side surfaces are painted white. Table 2 shows the results of this measurement. The r.m.s variation of light yield are 2.2% for the tile/fiber from unpolished sample, and is 2.8% for those from the other sample. The response maps for these samples are shown in Figures 12 and 13. We see that polishing the groove makes the uniformity worse over a tile.

sample	response uniformity (R.M.S. [%])
with polish	2.81 ± 0.17
without polish	2.15 ± 0.13

Table 2: Response uniformity of a tile with and without polish.

4.4 Responses near the fiber groove

In order to study the responses at points inside, outside and near the fiber groove, we have scanned a tile finer along a line from the tile center to a corner. For this study we have used a collimator which is 2 mm in diameter. Sample tiles are 80 mm square and 6 mm thick. The concentration of WLS fiber is 60 ppm. Four types of tiles have 1, 2, 3, and 4 turn fibers corresponding to 1, 2, 3 and 4 mm deep fiber grooves, respectivly. The results of these scannings are shown in Figure 14 with closed circles. We plot the discrepancys of pulse height at the scanning points from that on the center of the tile.

The light yield outside the groove is the same as that at the center of the tile to within 2%. The light yield is considerably smaller on the fiber groove where the tile is thinner, and the compensation of the decreased response is necessary, in particular for the tiles with 3 and 4 mm deep fiber grooves. We can restore the light yields on the grooves by adding a small amount of scintillating material, same as for SCSN81, into the WLS fibers. Its concentration is changed depending on the depth of the fiber groove: We use 0.5 ppm for a 2 mm deep groove, 1.5 ppm for a 3 mm and 7 ppm for a 4 mm. The results after the compensation are shown in Figure 14 with open circles. We can achieve better responses with this method.

4.5 Transverse response uniformity and the fiber length

As we mentioned earlier, we can obtain more constant responses for different tile sizes by adjusting the fiber length. We want to make sure that the transverse response uniformity within a tile does not strongly depend on the length of a WLS fiber in a tile. We have mapped the tiles with a half integer (1/2, 1, 3/2, 2, 5/2, 3, 4) turns of WLS fibers. For 1/2 turn fiber, the depth of the fiber groove is 1 mm, for 3/2 turns it is 2 mm, and for 5/2 turns it is 3 mm. All tiles are 80 mm square and 6 mm thick, and their grooves are not polished. The tile edges are painted white with BWP and tiles are wrapped in aluminized mylar. The responses are measured at 100 points in each tile. Figures 15 shows the responses for the tile with a 2-turn WLS fiber. The r.m.s. is about 2.5%. Figure 16 summarizes the transverse uniformity for the tiles with different fiber lengths. The tile with a 1/2 turn WLS fiber showed a non-uniform response of 8.5 % in r.m.s.. The non-uniformity excluding the points on the groove is about 5 %. The non-uniformity over a tile is about 2 % for a tile with a 2 turn fiber, about 3.7 %

for a 3 turn and about 6 % for a 4 turn. The non-uniformities excluding the points on the groove for these tiles are about 2 %.

A tile with a deeper groove gives more non-uniform rsponse as already mentioned. Then we have mapped the tiles with 2, 3, and 4 turns of WLS fibers in which scintillating material is added to improve the decreased response on the fiber groove. The results are also plotted in Figure 16 with squares. For the tiles with a 3 and a 4 turn fiber the non-uniformities over a tile are less than 2.1 %.

5 Conclusions

The response of tile/fiber system with multi-turn WLS fiber was made uniform longitudinally and transversely.

The light yield from a tile/fiber system decreases with increasing tile size. It was 7.3 pes for 80 mm square tile and 2 pes for 250 mm suare tile with 4 turns 30 ppm Y7 fiber. We adjusted the length of a WLS fiber within a tile according to the tile size to obtain a constant light yield for tiles with different sizes. Thus we achieved the longitudinal response uniformity of 3% in r.m.s. keeping the light yield larger than 2.5 photoelectrons per minimum ionizing particle.

We found that it is effective for getting uniform response over a tile to paint white the tile side surface and to leave the fiber groove unpolished. For a tile with a deeper groove, we compensated the decreased response around the groove by adding scintillating material into the WLS fiber. Thus we obtained transverse response uniformity over a tile less than 2.5%.

References

[1] CDF collaboration, CDF Plug Upgrade (Draft 1), (1992).

[2] Solenoidal Detector Collaboration, Technical Design Report, SDC-92-201, (April 1992).
SDC tile/fiber calorimeter group, Calorimeter conceptual design, tile/fiber scintillator option, (September 1991).

[3] T. Hasegawa *et al.*, Nucl. Instr. Methods A311 (1992) 498-504.

[4] T. Kamon *et al.*, Nucl. Instr. Methods A213 (1983) 261.

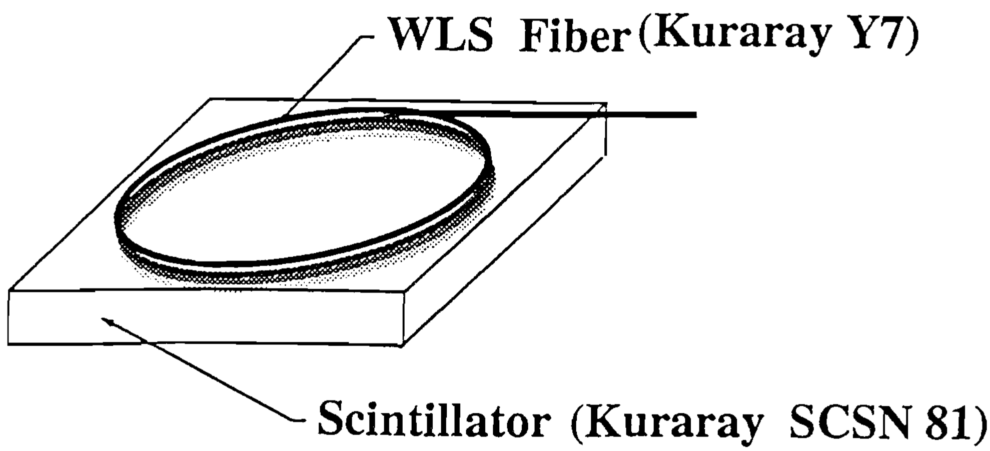

Figure 1: A scintillation tile and a muti-turn wavelength shifting fiber system.

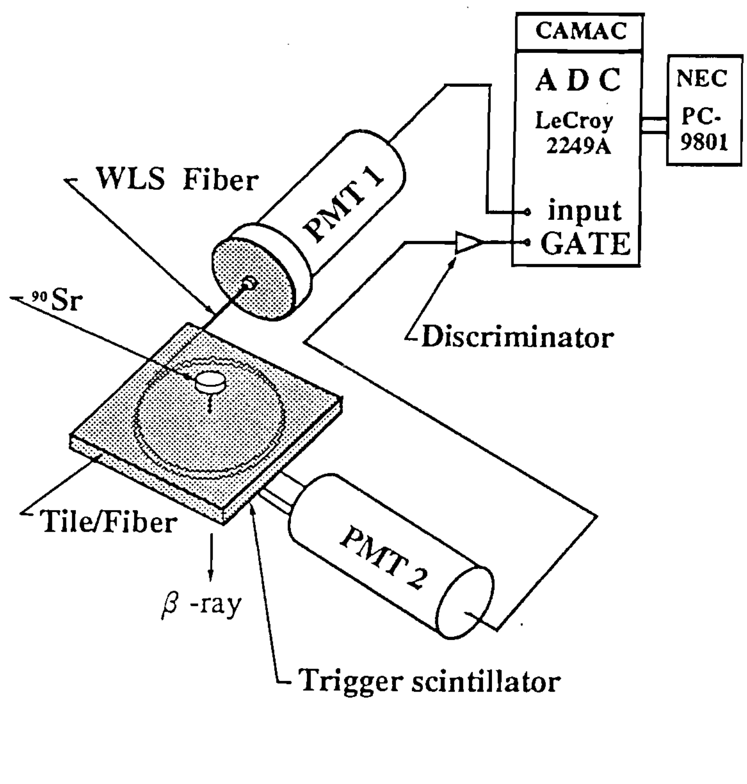

Figure 2: Experimenal setup for light yield measurement.

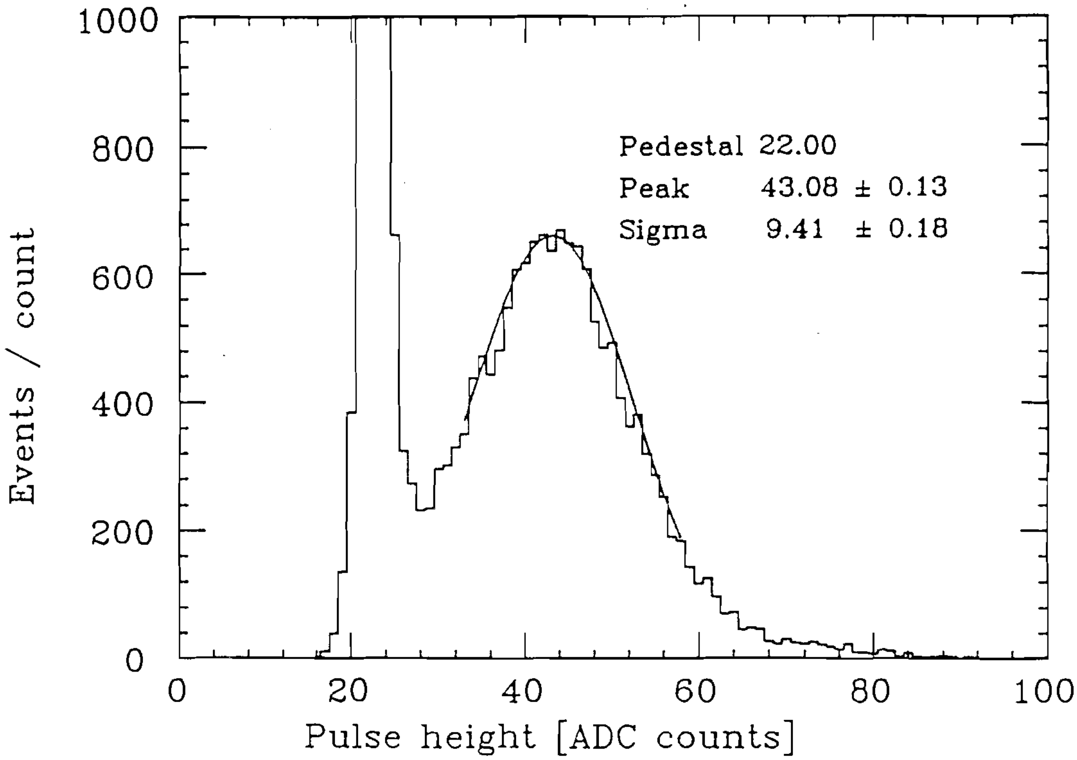

Figure 3: Single photoelectron peak.

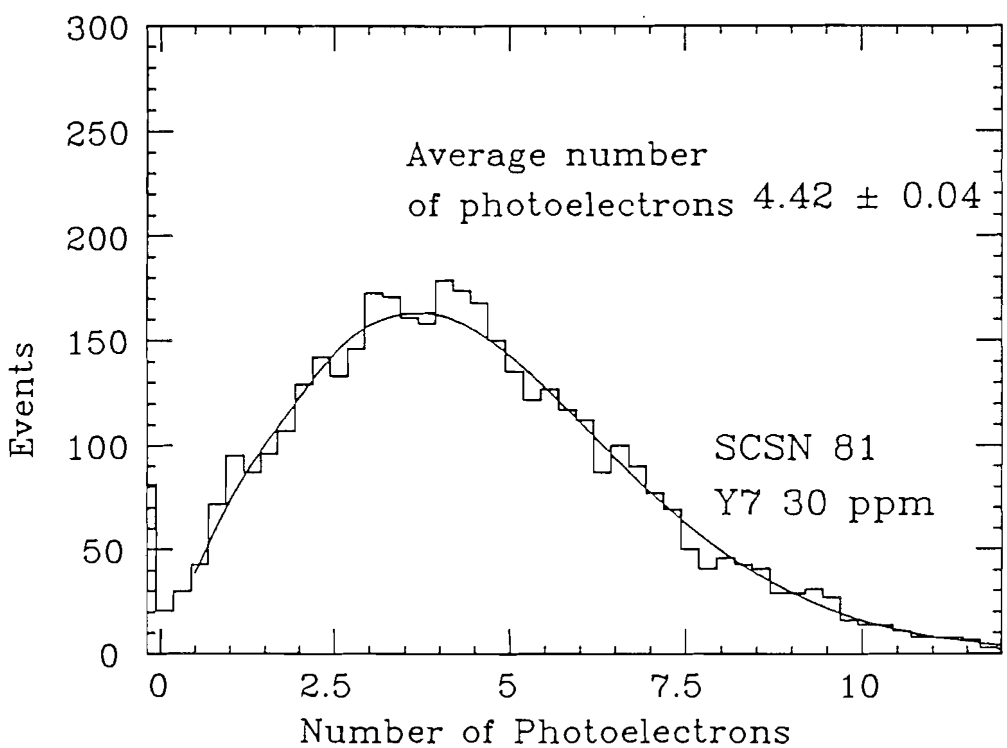

Figure 4: A typical pulse height distribution.

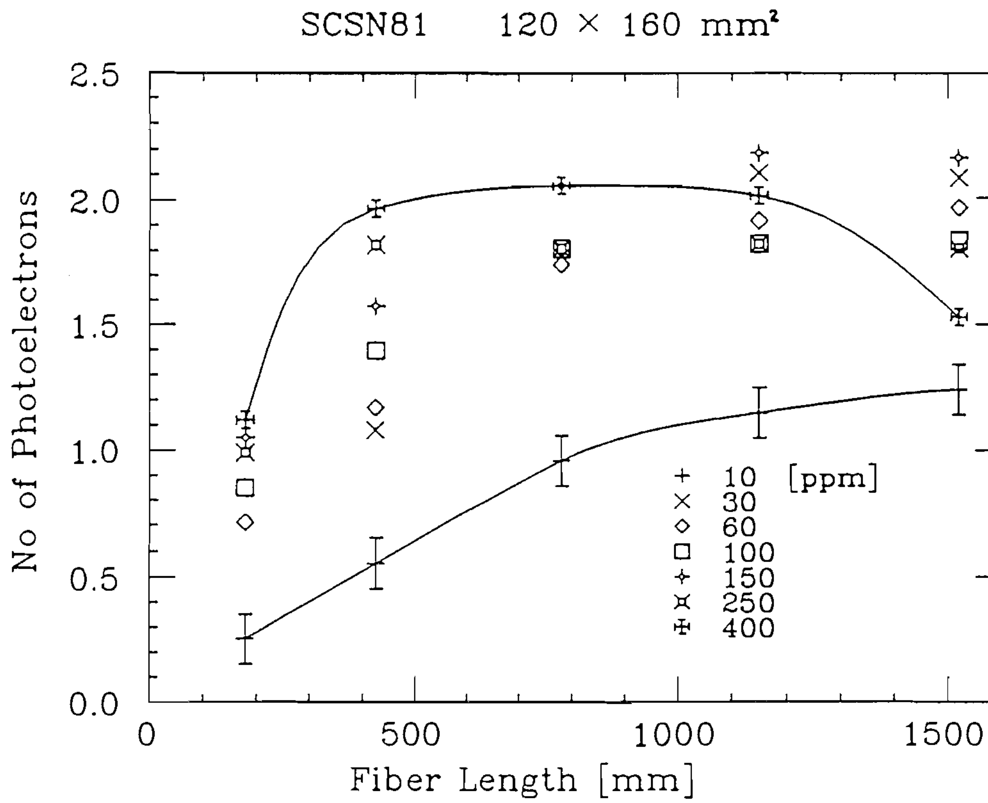

Figure 5: Light yield as a function of the fiber length within a tile for various wavelength shifter concentration.

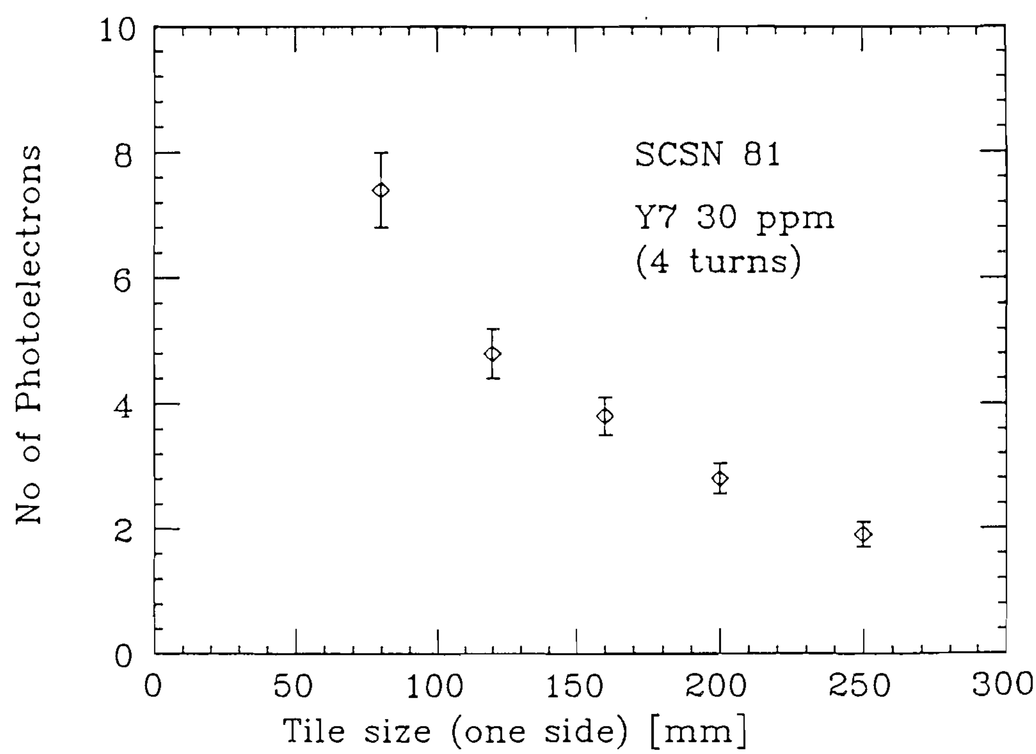

Figure 6: Light yield as a function of the tile size.

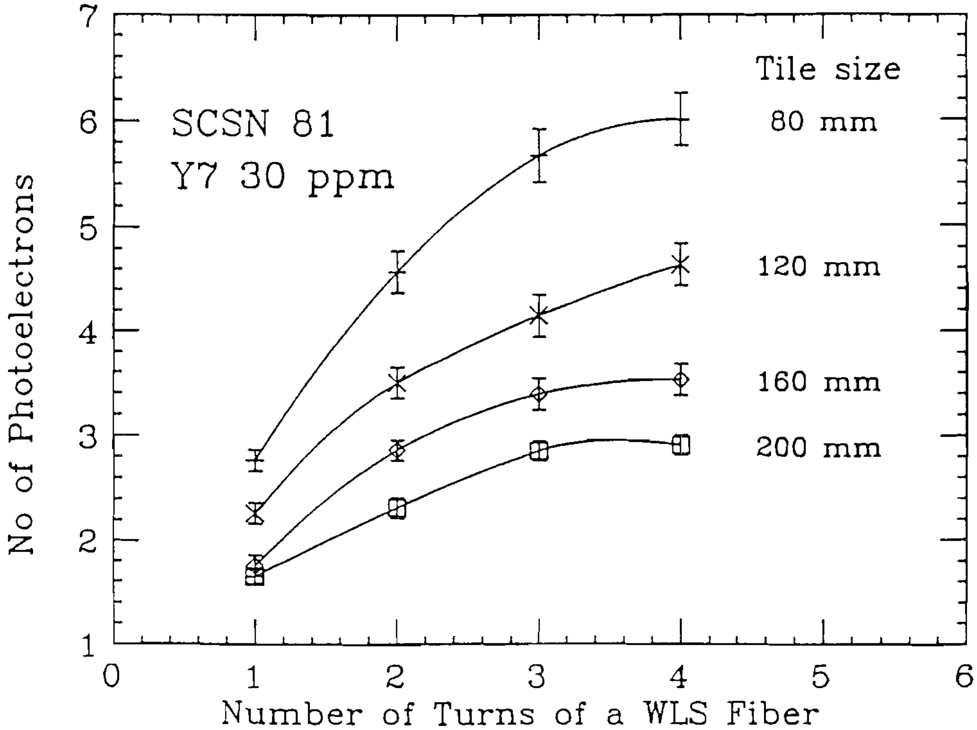

Figure 7: Light yield as a functions of the fiber length for tiles with various sizes.

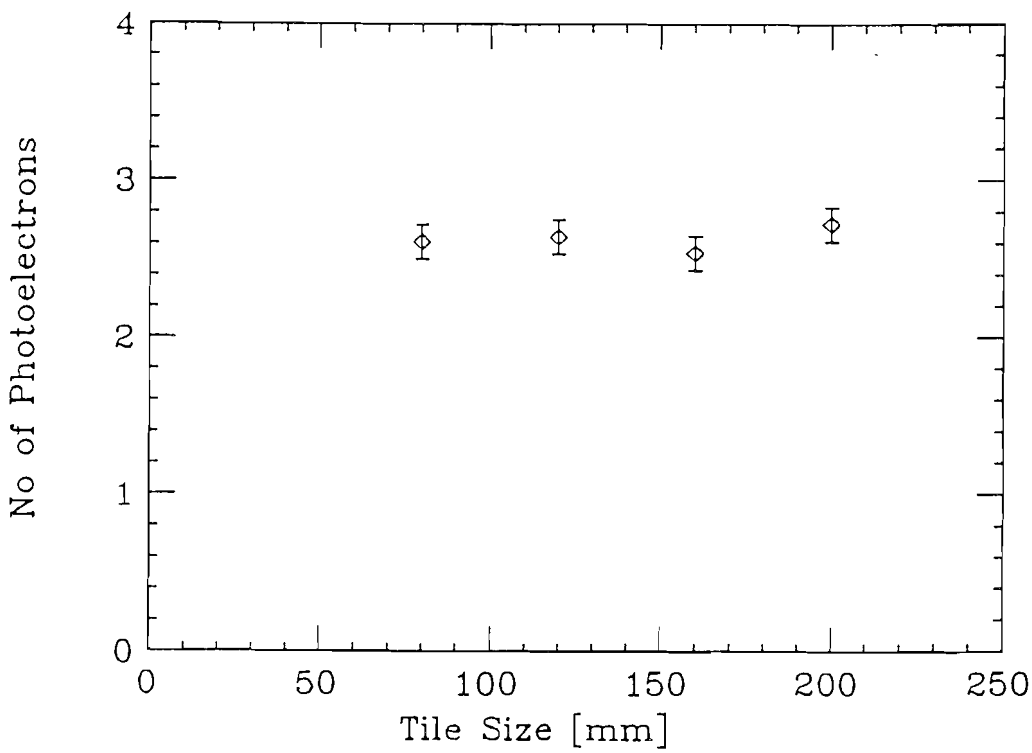

Figure 8: Light yield for tiles with different sizes after the fiber length adjustment explained in the text.

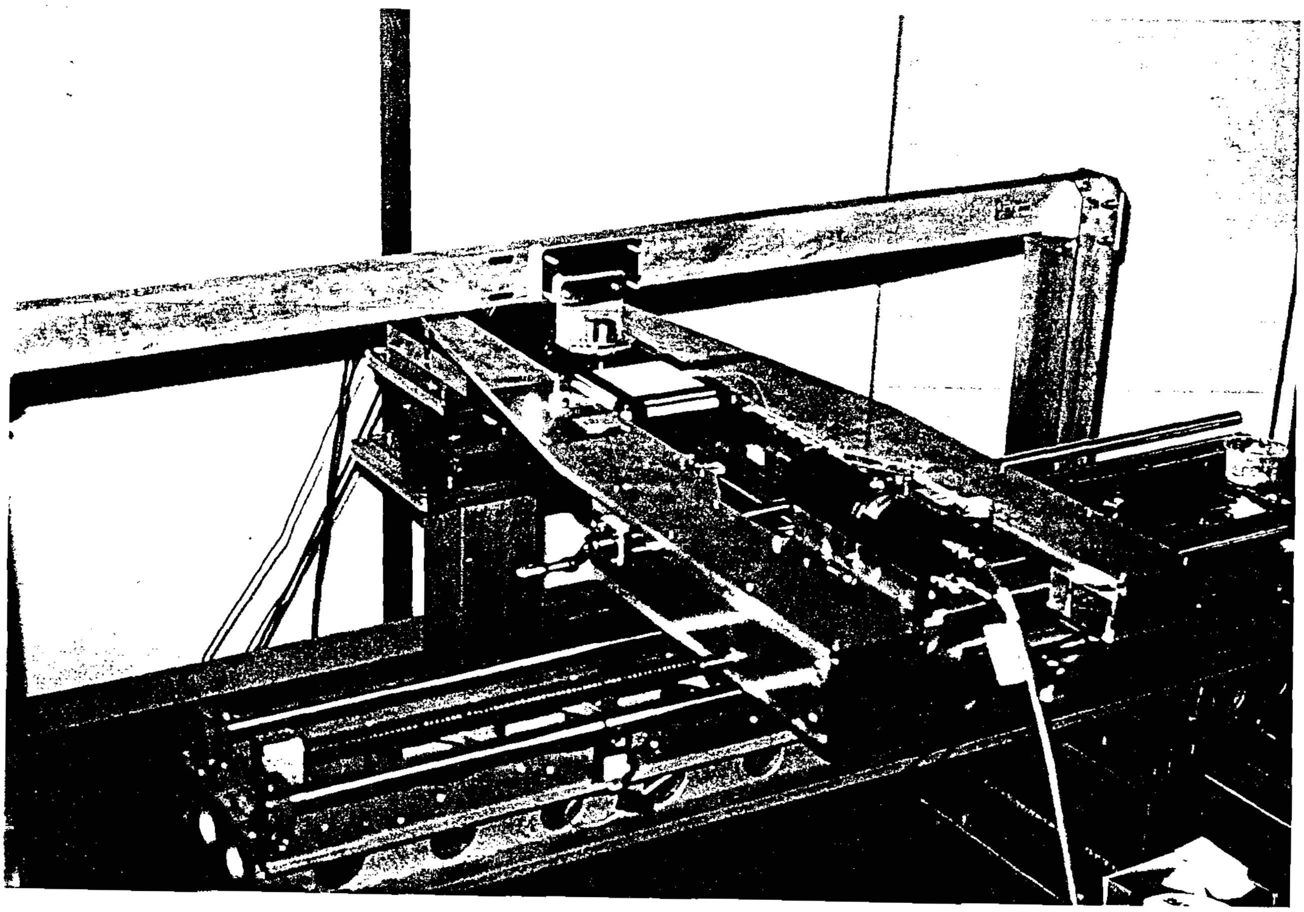

Figure 9: Automatic scanning system for the transverse uniformity measurement.

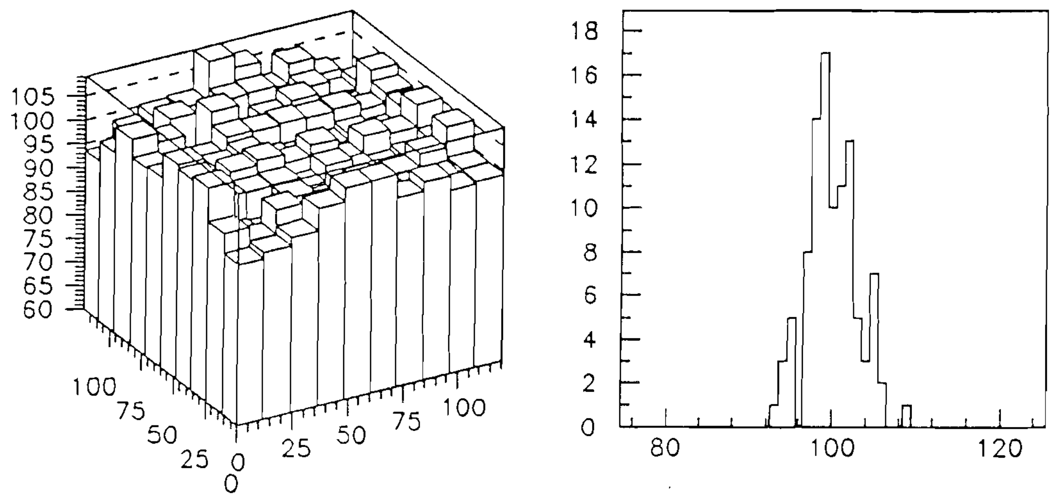

Figure 10: Response map for sample A.

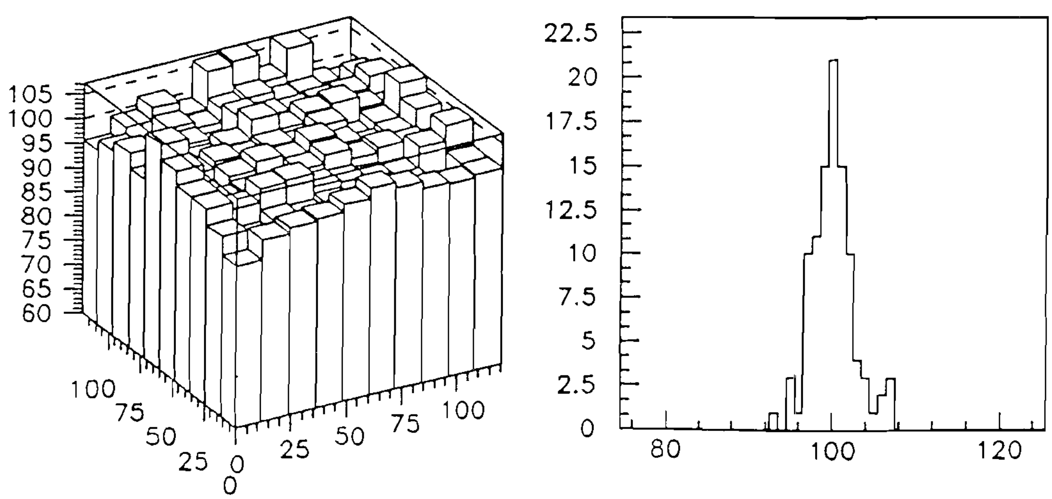

Figure 11: Response map for sample B.

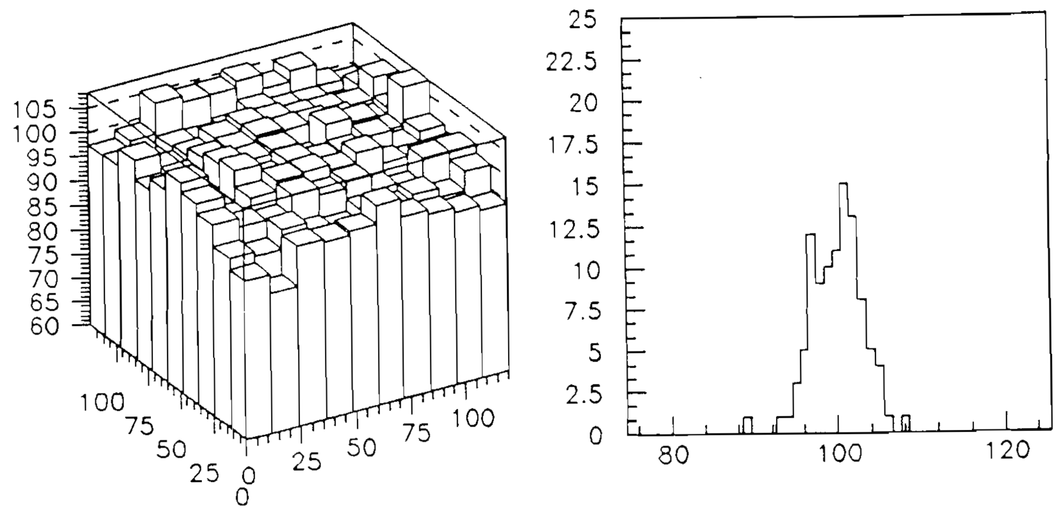

Figure 12: Response map for the tile with a polished groove.

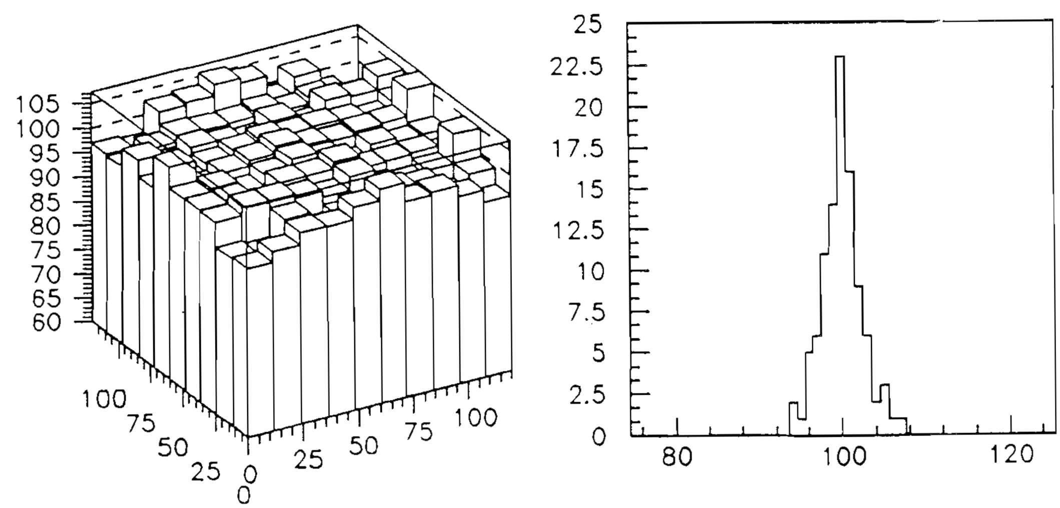

Figure 13: Response map for the tile with a non-polished groove.

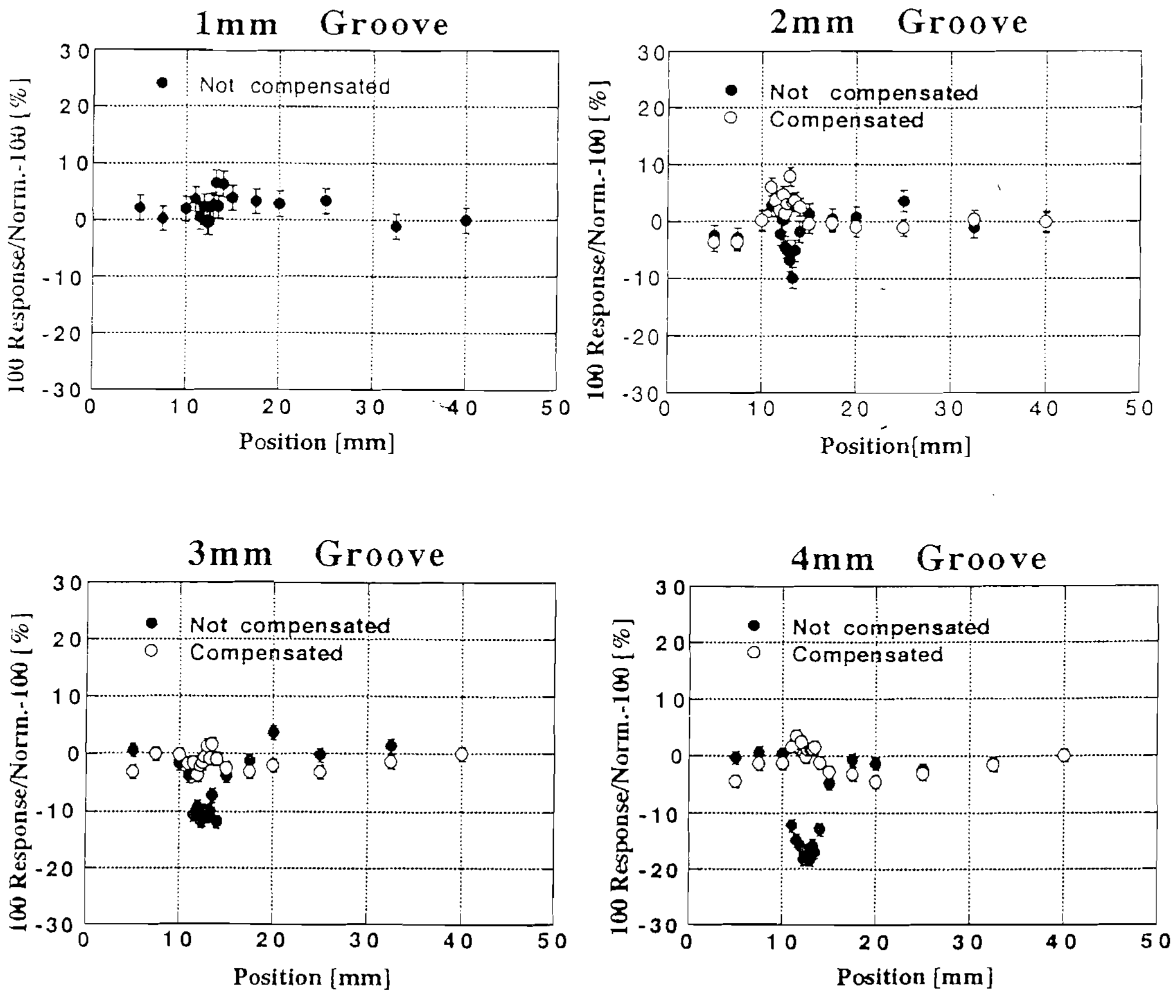

Figure 14: Responses along a line from the tile center to a corner.

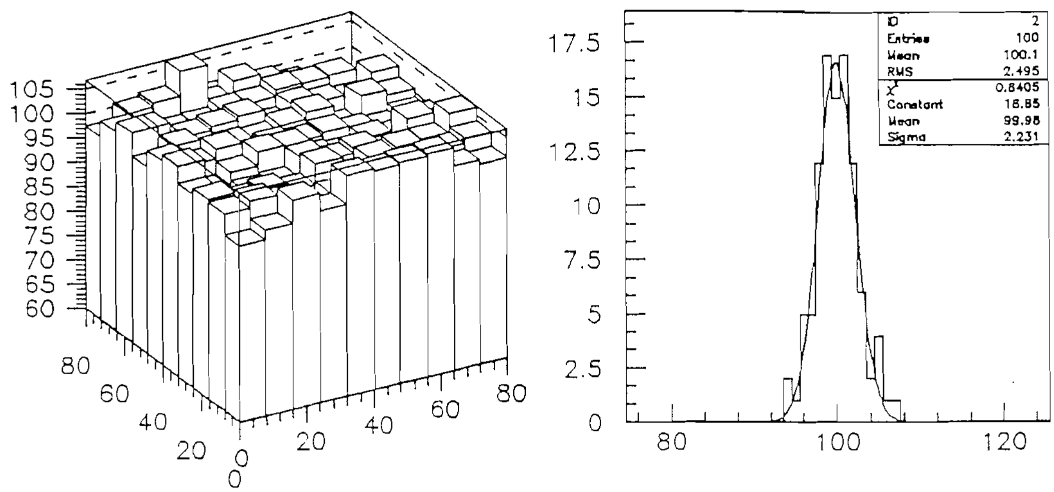

Figure 15: Response map for a tile with 2-turn WLS fiber.

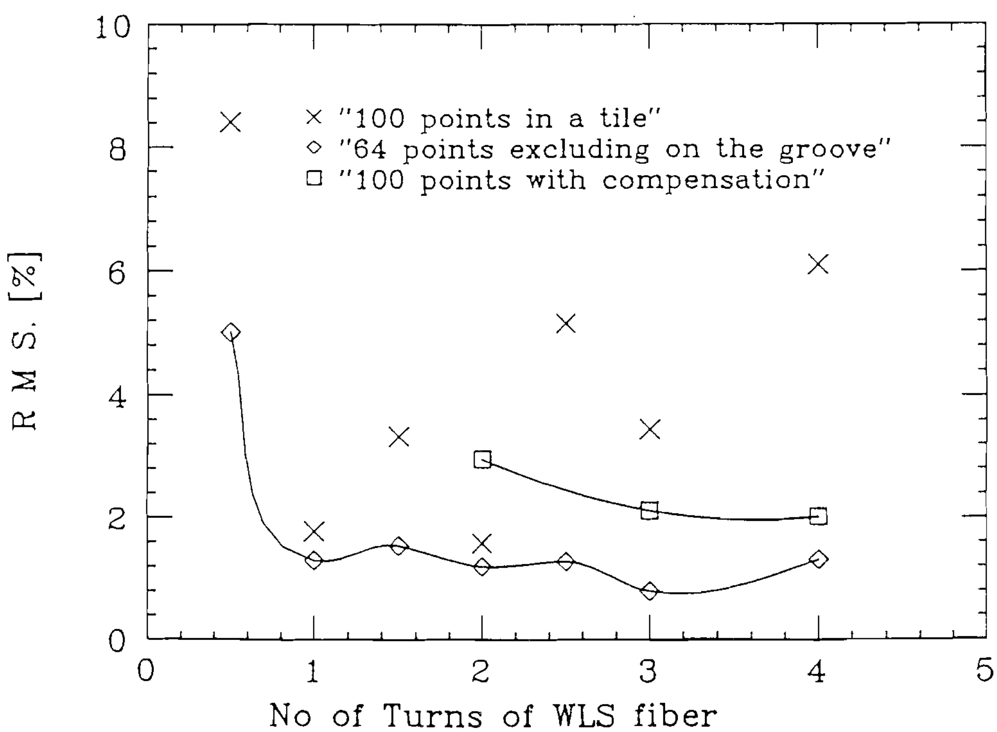

Figure 16: Transverse response uniformity as a function of the fiber length.