ELSEVIER

Nuclear Instruments and Methods in Physics Research A 420 (1999) 48–61

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

Mass production of tile/fiber units for the CDF plug upgrade EM calorimeter

S. Aota[a], T. Asakawa[a], K. Hara[a], E. Hayashi[a], S. Kim[a], K. Kondo[a], T. Kuwabara[a], S. Miyashita[a], H. Nakada[a,*], I. Nakano[a], Y. Seiya[a], T. Takebayashi[a], K. Takikawa[a], H. Toyoda[a], T. Uchida[a], K. Yasuoka[a], M. Mishina[b], J. Ioveri[c]

[a] *Institute of Physics, University of Tsukuba, Ibaraki 305, Japan*
[b] *Fermi National Accelerator Laboratory, Japan*
[c] *Waseda University, Japan*

Received 8 June 1998

Abstract

We have fabricated scintillating tile/fiber units for the CDF plug upgrade electromagnetic calorimeter. The total number of tile/fiber systems amounts to $\sim 23\,000$. We describe the quality control tests of scintillator plates, optical fibers, and tile/fiber units which we placed at various stages in the fabrication procedures. We have completed the production retaining the tile/fiber units which satisfy our requirements. © 1999 Published by Elsevier Science B.V. All rights reserved.

PACS: 29.40.Mc; 29.40.Vj

Keywords: Calorimeter; Scintillator; Tile/fiber; Mass production; Quality control; CDF

1. Introduction

The CDF (Collider Detector at Fermilab) plug calorimeter will be upgraded in 2000 replacing the gas calorimeter [1,2]. The new plug electromagnetic (EM) calorimeter was designed to take full benefits of the accelerator upgrade. It is a plastic-scintillator-based sampling calorimeter consisting of scintillator plates with embedded optical readout fibers (tile/fiber) and lead absorber plates. With this new calorimeter, substantial improvements are expected in fast response, small dead space, and good energy resolution comparing to the previous gas calorimeter. We performed R&D for the new plug EM calorimeter from October 1990 to June 1993 [3–5]. The mass production of tile/fiber units was started in October 1993 and completed in February 1994. We monitored and controlled the quality of scintillating tiles and optical fibers at various stages in the production. The results of our quality checks satisfy the criteria required for good energy resolution and good response linearity.

* Corresponding author. Tel.: + 81 298 53 4270; fax: + 81 298 53 4491; e-mail: housai@hep.px.tsukuba.ac.jp.

PII: S0168-9002(98)01135-8

We report on our quality control and the results in this note.

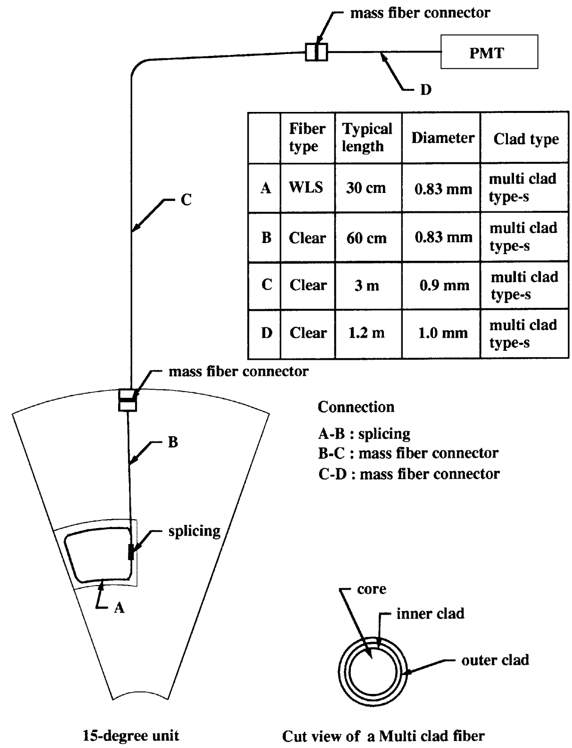
We begin by describing the CDF EM calorimeter and our requirements for the tile/fiber system in Section 2. A number of our quality control tests performed during the tile/fiber production are described in Section 4. The conclusion is given in Section 5.

2. CDF plug electromagnetic calorimeter

2.1. Tile/fiber

The CDF tile/fiber EM calorimeter consists of 23 layers of sampling devices of a scintillating tile with an embedded wavelength shifting fiber (WLS fiber), 23 lead absorber plates clad with stainless-steel plates, and a shower maximum position detector installed behind the 5th layer. The sampling tile/fiber layer is divided to 24 units. One unit covers an azimuthal angle of 15° as shown in Figs. 1 and 2, and is called "15° unit" hereafter. A 15° unit consists of 20 tiles for the 1st to 15th layers and 18 tiles for the 16th to 23rd layers, plastic plates at top and bottom, and two sheets of polystyrene-terephthalate (PET) film used as reflector. A tower of the calorimeter has a projective tower geometry and covers a certain solid angle with respect to the nominal collision point. Tiles within a tower have a tile number, which is the tower number, but the physical sizes are different in depth in the tower. The tile number assignment is given in Fig. 2.

We chose Kuraray SCSN38 as the material of scintillating tiles and Kuraray Y11 WLS and clear fibers. These fibers with strong-type cladding are multi-clad-type fibers and have polystyrene for the core, polymethylmethacrylate for the inner clad, and fluorinated polymer for the outer clad. A Y11 WLS fiber with a diameter of 0.83 mm is thermally spliced to a clear fiber with the same diameter [6]. The clear fiber is then connected to another clear fiber of 0.90 mm diameter through a mass fiber connector. The 0.90ϕ fiber is connected further to another clear fiber of 1.0 mm diameter through a mass fiber connector (see Fig. 1). These clear fibers have plastic sheath for protection. The other end of the WLS fiber is mirrored by aluminum sputtering with a cover of MgF_2 [7]. Light yielded in a scintillating tile is collected by the WLS fiber embedded in the tile, transmitted through the clear fibers, and finally read out with a photomultiplier tube (PMT).



	Fiber type	Typical length	Diameter	Clad type
A	WLS	30 cm	0.83 mm	multi clad type-s
B	Clear	60 cm	0.83 mm	multi clad type-s
C	Clear	3 m	0.9 mm	multi clad type-s
D	Clear	1.2 m	1.0 mm	multi clad type-s

Fig. 1. A schematic figure of a 15° unit and the readout path.

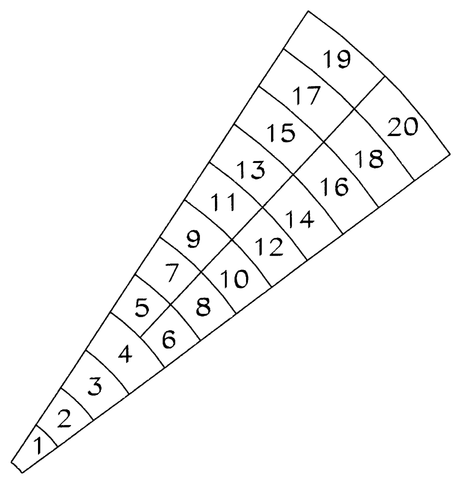


Fig. 2. Tile number assignment in a 15° unit. A 15° unit consists of 20 tiles for layers 1–15 and 18 tiles for layers 16–23.

2.2. Requirements

The energy resolution is given by

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{\sigma_1}{\sqrt{E}}\right)^2 + (\sigma_2)^2, \quad (1)$$

where the first term $\sigma_1/\sqrt{E}$ comes from the sampling fluctuation and the photostatistics of PMTs, and the second term σ_2 comes from the non-uniform response of the calorimeter. We have estimated the sampling fluctuation for 4.5 mm thick lead plates to be $14\%/\sqrt{E}$ using a shower simulation [1,2]. The new EM calorimeter is required that the stochastic term σ_1 should be less than 16% and the constant term σ_2 be less than 1%. Non-linearity of the calorimeter is required to be less than 1% in the energy range between 10 and 400 GeV. To fulfill the above criteria we require

1. light yield from a tile/fiber be more than 3 photoelectrons (pes) per minimum ionizing particle (MIP),
2. response non-uniformity within a tile be less than 2.5%,
3. response variation of tiles within a tower be less than 10%, and
4. a total of light leakage from a tile to the adjacent tiles be less than 3.5%.

More details are described in Refs. [1,2].

3. Light yield measurement

3.1. Experimental setup

A typical experimental setup for our light yield measurement is shown in Fig. 3. We excite a scintillating tile with a ^{90}Sr β-ray source. The source has a lead collimator of 5 mm in diameter. Light from the tile/fiber is converted to electric signal by a PMT (Hamamatsu H1161GS or R580-17 green-extended type[1]). The signal from the PMT is digitized by a LeCroy 2249A CAMAC ADC module. The trigger counter which is placed beneath the tile/fiber consists of a trigger scintillator (2–5 mm in diameter), an acrylic light guide, and two PMTs (Hamamatsu H1161). We use a coincidence between signals from both the PMTs as the trigger signal in this measurement.

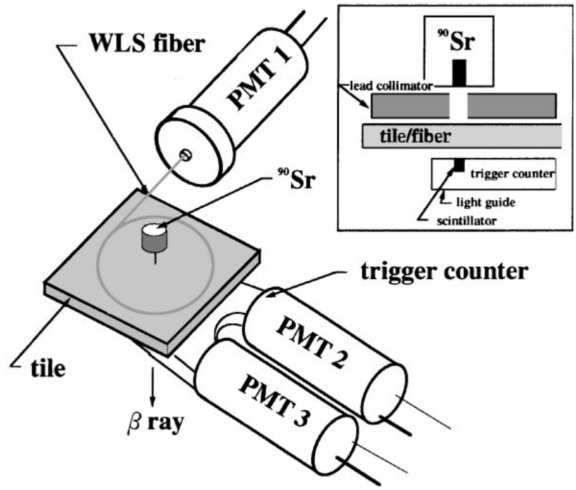


Fig. 3. Typical setup for the light yield measurement.

3.2. Light yield

We estimate the light yield from the tile/fiber in terms of average number of photoelectrons produced from the PMT photocathode. The average number of photoelectrons is more universal than average current or average electric charge from PMTs; it does not depend on the gain of the PMT or the intensity of the source, but depends on the light yield and the quantum efficiency of the photocathode.

We measured light yield from scintillator plates and tile/fiber systems in the following way: 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 the single photoelectron. The pulse height for the single photoelectron is measured

[1] These are green-extended-type PMTs and have a quantum efficiency typically 15% higher than standard PMTs of H1161(R329) or R580 for green light of approximate 500 nm wavelength. H1161GS has more dynode stages than R580-17, thus has a higher gain.

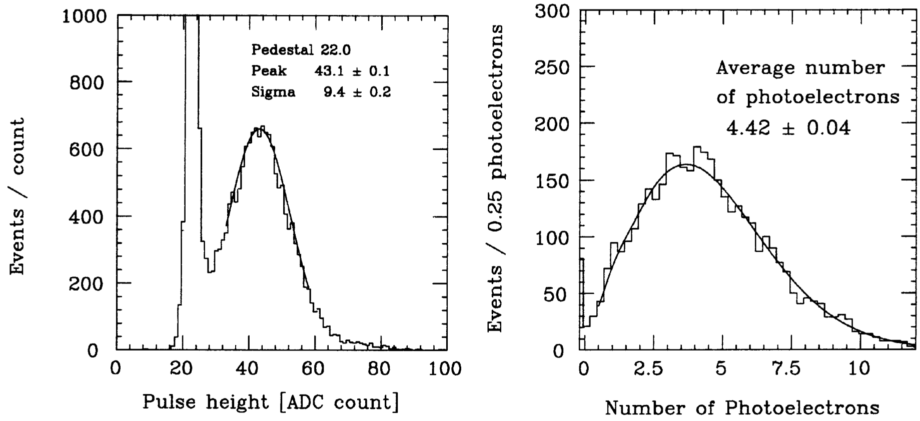


Fig. 4. A single photoelectron distribution (left) and a pulse height distribution in units of the single photoelectron peak (right).

with the same experimental setup by sufficiently reducing the light intensity. In the measurement of a single photoelectron pulse height, light yield is typically ~ 0.1 photoelectrons. Fig. 4 (left) shows a typical pulse height distribution obtained in this measurement. The first peak at 22 ADC counts is the pedestal and the second peak at 43 ADC counts corresponds to the 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 curve is shown in the figure. The next step is to determine the average number of photoelectrons from the pulse height distribution. The average number of photoelectrons (N_{pe}) is given by

$$N_{pe} \equiv \frac{X_{ave} - X_{ped}}{X_{spp} - X_{ped}}, \tag{2}$$

where X_{ave} is the average ADC counts of the given pulse height distribution, X_{spp} is the single photoelectron peak counts, and X_{ped} is the pedestal counts. Fig. 4 (right) shows a typical pulse height distribution in which the x-axis is scaled in units of the single photoelectron peak.

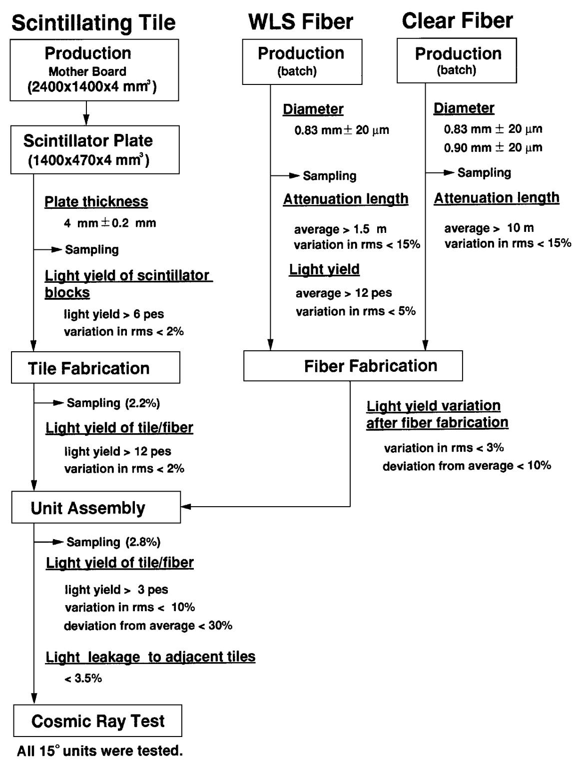


Fig. 5. The procedure of the mass production and the quality control performed during the production.

4. Quality control

Shown in Fig. 5 is the procedure of the tile/fiber production. We checked the quality of tiles and fibers at several stages in the mass production. We begin by describing the scintillator production and the quality control.

4.1. Scintillator plate production

Scintillator boards, "*mother boards*", are produced by Kuraray. The size of the mother board is 2400 mm × 1400 mm × 4 mm. We produced 240 mother boards from 10 lots in total. The mother board production was done in two periods; in the first period, 60% of the total were made and in the second the rest were made. From each of mother boards we cut out four pieces of scintillator plates (470 mm × 1400 mm × 4 mm). Light yield of the scintillator plate mainly depends on the plate thickness and the chemical concentration of the wavelength shifter. To ensure uniform response over a tile/fiber system, these two characteristics should be uniform. We checked thickness and response uniformity of scintillator plates. We also compared the quality of scintillator plates produced in the two different periods each other.

4.1.1. Plate thickness measurement

The nominal thickness of scintillating tiles is 4.0 mm. We required the thickness of scintillator plates should be 4.0 mm with a tolerance of 0.2 mm.

The experimental setup for the thickness measurement is shown in Fig. 6. The distance between the top and bottom surfaces of the scintillator plate is measured with differential transducers with a resolution of ~ 5 μm. In the system there are five pairs of transducers with an interval of 25 cm. When the scintillator plate is scanned along the direction parallel to the shorter (longer) side of the plate, the plate thickness was measured at 5 (2) points with 5 (2) pairs of transducers at the same time (see Fig. 7). We recorded the plate thickness at every 1 cm during the plate scan. Peripheral area of scintillator plates (5 cm or less inside the plate edges) was excluded in this measurement; the thickness in that area was known to be non-uniform and the region was cut out in the tile production. The plate thickness was measured at 482 points in each plate.

The measured distribution of the plate thickness is shown in Fig. 8. We obtained the acceptable results that the average thickness is 3.983 mm and the rms variation is 0.065 mm (1.6%). The results are summarized in Table 1.

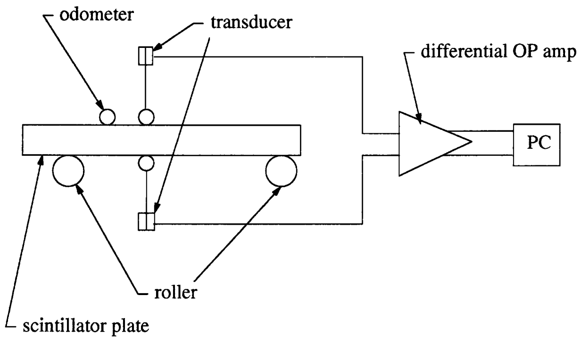


Fig. 6. Experimental setup for the plate-thickness measurement.

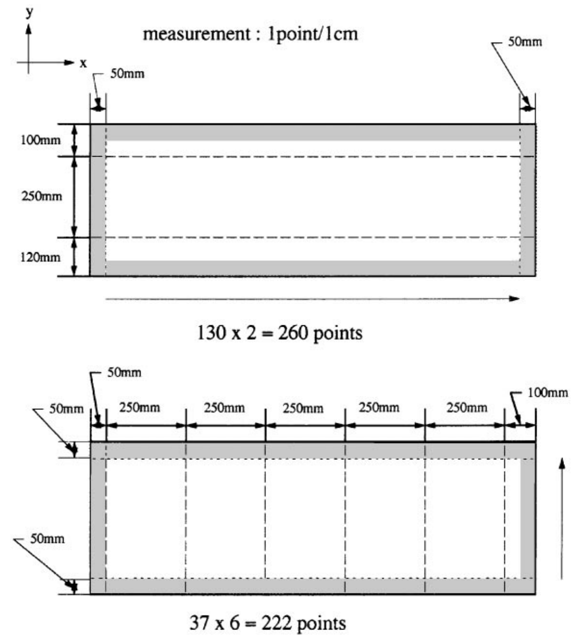


Fig. 7. The measured points in a plate. Plate thickness is measured along the dashed lines. The shaded area was excluded in the measurement.

4.1.2. Light yield of scintillator plates

We sampled scintillator blocks with dimensions of 20 mm × 30 mm × 4 mm from scintillator plates and measured the light yield to check the uniformity of the wavelength shifting material. We sampled (i) one scintillator block per mother board in order to monitor the variation between different mother boards and (ii) 12 blocks per mother board per lot

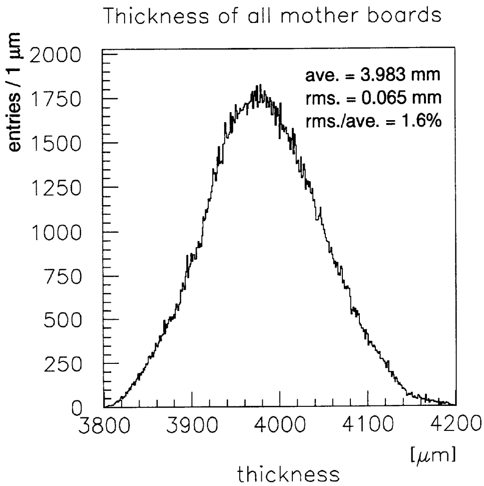


Fig. 8. A distribution of the plate thickness for all mother boards. We obtained the average thickness of 3.983 mm and the RMS variation of 0.065 mm.

Table 1
Summary of the plate thickness measurement

Production	1st (60%)	2nd (40%)	Total
Ave. thickness (mm)	4.0	4.0	4.0
Variation (%)	1.6	1.5	1.6

in order to monitor the variation within a mother board. The light yield of the scintillator plate depends on the plate thickness. In order to extract the variation of the light yield due to the non-uniformity of the wavelength shifter, we scaled the measured light yield to that expected for the nominal plate thickness of 4 mm using the measured thickness.

The experimental setup is shown in Fig. 9. We used an electromagnetic (EM) shutter and a quartz glass in front of the PMT so that we could keep the PMT high voltage on and hence keep the PMT gain stable during the measurement. The light intensity of the sample block was reduced to 5% by a neutral density (ND) filter and air gaps between the sample block and the PMT. Uncertainty of the light yield measurement with this system is 1%. In this measurement we required that the light yield of a block should be more than 6 pes per MIP, and the

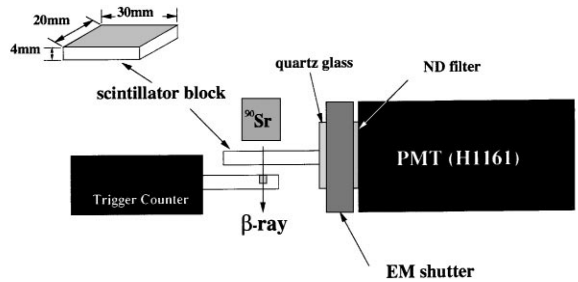


Fig. 9. Experimental setup for the light yield measurement of scintillator blocks.

variation after the block thickness correction be less than 2%. The results of this measurement are shown in Fig. 10: (a) the reproducibility of this measurement, (b) the light yield of scintillator blocks before the thickness correction, (c) the thickness of scintillator blocks, and (d) the light yield after the thickness correction. The light yields of all sampled blocks were measured to be more than 7.0 pes. The variation of the thickness-corrected light yield was 1.7% after subtracting 1% of the systematic error. We summarize the results in Table 2. These results satisfy our requirements.

4.2. Fiber production

Fibers were produced in "*batch*" in which preforms with the same chemical mixture were used. Fibers from the same batch, therefore, can be thought to have almost the same chemical quality. In order to control the quality of fibers, we checked

1. diameter of clear and WLS fibers,
2. light attenuation length of clear and WLS fibers, and
3. light yield of WLS fibers with a standard scintillating tile.

We use clear fibers with three different diameters ($\phi = 0.83$, 0.90, 1 mm) as mentioned in Section 2. We report on our quality test for the WLS fibers and the 0.83ϕ and 0.90ϕ clear fibers in this note.

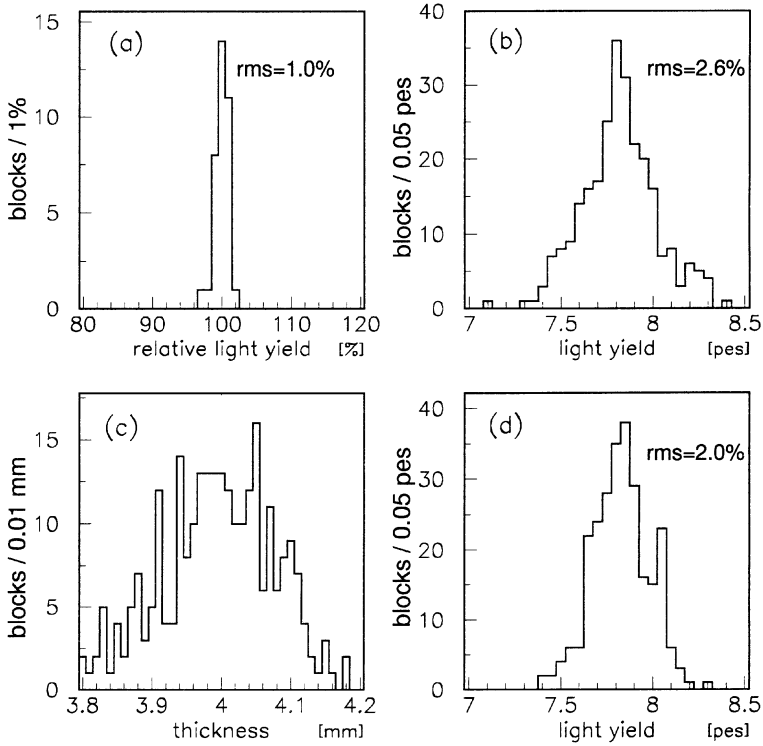


Fig. 10. Results of the light yield measurement of scintillator blocks: distributions of (a) the reproducibility of the measurement, (b) the light yield of scintillator blocks, (c) the measured block-thickness, and (d) the thickness-corrected light yield are shown.

Table 2
Summary of the light yield measurement of scintillator blocks. The minimum light yield, the light yield variation in all samples, and our requirements are listed

Production	1st (60%)	2nd (40%)	Total	Requirement
Minimum light yield (pes)	7.0	7.5	7.0	> 6
Variation (%)	1.8 ± 0.1	1.5 ± 0.2	1.7 ± 0.1	< 2

Table 3
Nominal fiber diameters and our requirements

Fiber	Nominal diameter (μm)	Tolerance (μm)
WLS	830	± 20
Clear	830	± 20
Clear	900	± 20

4.2.1. Diameter

Nominal diameters and our requirements on the fiber diameters are summarized in Table 3. For WLS fibers, we sampled a 3 m long fiber out of every 100 m of WLS fiber. The diameter of the fiber was measured at every 5 cm with a resolution of 0.1 μm. Fibers with diameters out of the specifications were rejected. For clear fibers, we cut the fibers after the fibers were covered. Therefore, we measured diameters of the fibers and marked the regions where the measured diameters were out of the specification. The bad regions were not used.

4.2.2. Light attenuation length

We measured light attenuation length of WLS fibers and clear fibers. We require that the attenuation length of the WLS fibers and the clear fibers

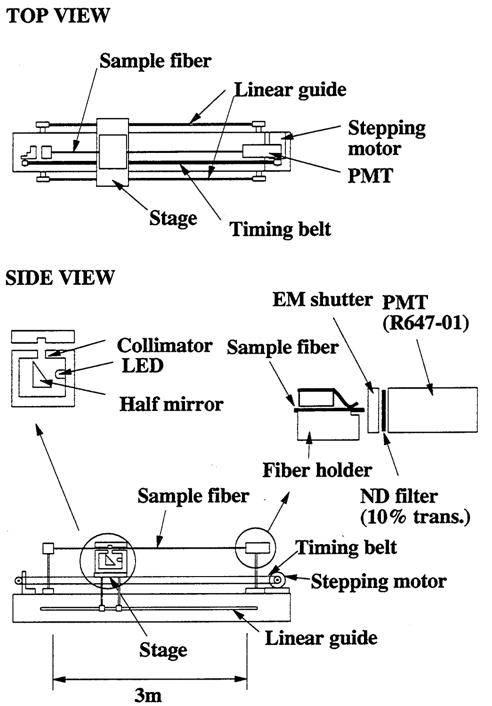


Fig. 11. Experimental setup for the attenuation length measurement of WLS fibres.

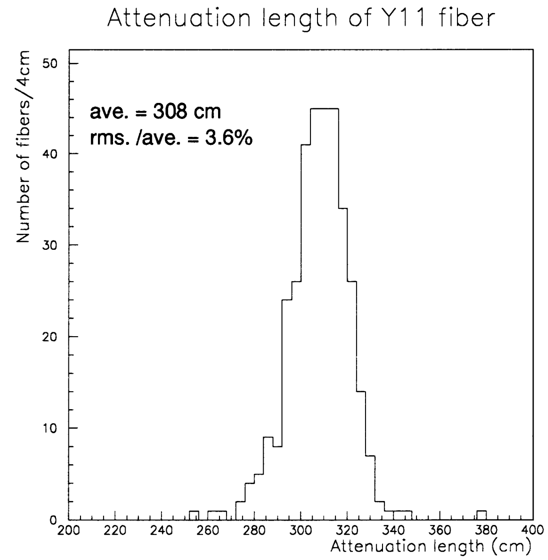


Fig. 12. A distribution of the attenuation length of 3 m long WLS fibers.

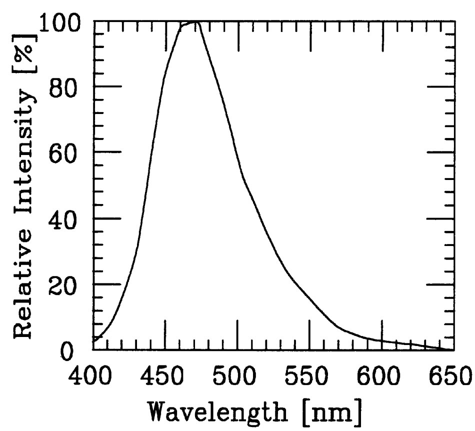


Fig. 13. A distribution of light intensity vs. wavelength of the halogen lamp used in the attenuation length measurement of clear fibers.

should be more than 1.5 and 10 m, respectively, and their variations be less than 15%.

For WLS fibers, we sampled a 4 m long fiber out of every 50 m of WLS fiber after the diameter measurement. The 4 m fiber was then divided into a 75 cm long fiber and a 3 m long fiber, which were used in the light yield and the attenuation length measurements, respectively. Shown in Fig. 11 is the experimental setup for the attenuation length measurement. The light intensity was measured by reading the current of a PMT (Hamamatsu R647-01) while exciting the fiber from the side with an LED at 5 cm intervals. Note that the wavelength of the LED lamp was $\sim$ 470 nm.

We obtained the attenuation length by fitting the plot of the light intensity vs. LED position with a single exponential function. The distribution of the attenuation length of the WLS fibers is shown in Fig. 12. The average attenuation length and its variation were measured to be 308 cm and 3.6% in RMS, respectively.

For clear fibers, we sampled a pair of 15 m long clear fibers at the beginning and the end of each batch. We use a halogen lamp as a light source. The wavelength distribution of the light from the halogen lamp is shown in Fig. 13. It has a peak at the wavelength around 470 nm and has broad tails. The light from the halogen lamp was injected into one end of the sample clear fiber, and the light intensity was measured at the other end by a spectrum analyzer at wavelengths of 500 and 670 nm. The fibers were then shortened to 3 m, and the light transmission was measured again. We calculated the attenuation length λ at a wavelength using the results obtained from the two fibers with the two different lengths as follows:

$$I_{15} = A\mathrm{e}^{-15/\lambda}, \qquad I_3 = A\mathrm{e}^{-3/\lambda},$$

$$\frac{I_{15}}{I_3} = \frac{A\mathrm{e}^{-15/\lambda}}{A\mathrm{e}^{-3/\lambda}} = \mathrm{e}^{-12/\lambda},$$

$$\lambda = -\frac{12}{\ln(I_{15}/I_3)}, \qquad (3)$$

where A is a constant, I_{15} and I_3 are the measured light intensities of the 15 m long and the 3 m long fibers, respectively. We obtained the average attenuation lengths of the clear fibers to be 9.3 m at a wavelength of 500 nm and to be 21.4 m at a wavelength of 670 nm and their variations to be 21% and 11%, respectively (see Fig. 14). By an interpolation of the two results obtained for the wavelengths of 500 and 670 nm, the attenuation length at 550 nm, which corresponds to the wavelength of light from WLS fibers, was estimated to be 12.9 m with the rms variation of 14%. These results satisfy our requirements.

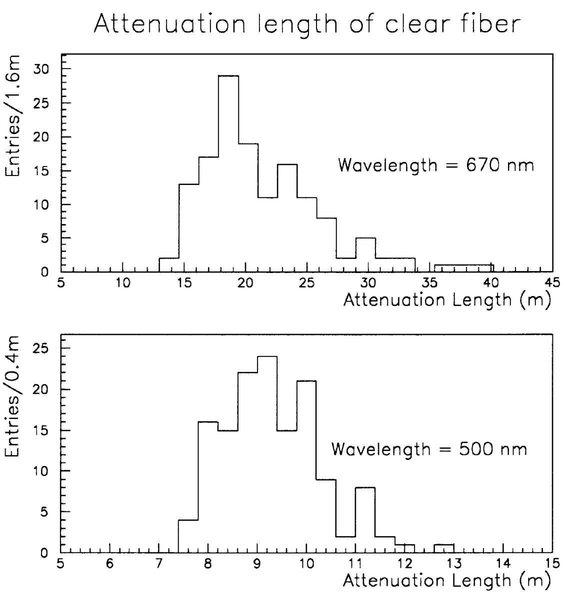


Fig. 14. Distributions of the attenuation length of clear fibers at wavelength of 670 nm (top) and at 500 nm (bottom).

4.2.3. *Light yield of WLS fibers*

We sampled a 75 cm long fiber out of every 50 m long WLS fiber in the fiber production. We measured the light yield of the sample WLS fibers using the experimental setup shown in Fig. 15. We inserted a sample WLS fiber in a standard scintillating tile (120 mm × 120 mm × 4 mm) and measured the light yield with the sample fiber with a PMT. We required the average light yield to be more than 12 pes and its variation to be less than 3% in this measurement.

The distribution of the light yield is shown in Fig. 16. The average light yield of the sample WLS

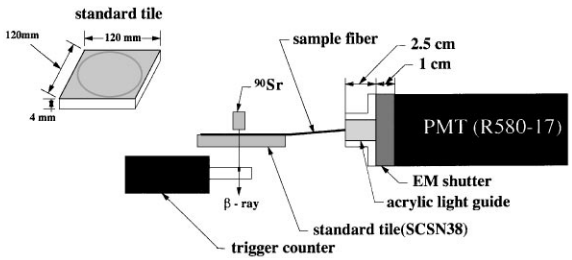


Fig. 15. Experimental setup for the light yield measurement of WLS fibers.

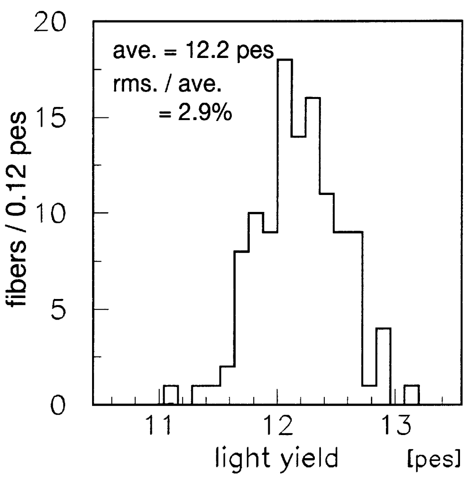


Fig. 16. A distribution of the light yield of WLS fibers.

Table 4
The results of the light yield measurement of the WLS fibers

	Result	Requirement
Ave. light yield (pes)	12.2	> 12
Variation (%)	2.9	< 3

fibers and the rms variation were measured to be 12.2 pes and 2.9%, which satisfy our requirements. We summarize the results in Table 4.

4.3. *Tile fabrication*

The scintillator plate was first cut into tiles with dimensions somewhat oversizing the required dimensions. We then performed fine cutting, carving the fiber groove, and painting white the four tile sides. After the tile fabrication, we sampled about 2% of the total in order to measure the response variation. We sampled tiles according to Table 5, the tile numbers being shown in Fig. 2. We sampled eight 15° units each from layers 6, 12 and 23, and one 15° unit each from other layers. From each of the sampled 15° units we sampled 12 tiles for layers 1 to 15 and 11 tiles for layers 16–23. In total, 513 tiles corresponding to 2.2% of the total were sampled.

We require the light yield to be greater than 3 pes per MIP for the tile/fiber with a WLS to clear fiber splicing and two fiber-to-fiber connectors including the attenuation in the fibers as mentioned in Section 2.

The experimental setup for testing the light yield of the tile is almost the same as one used for the test

Table 6

Order	Tile	Fiber	Light yield
0	Reference	Standard	r_0
·	·	·	·
i	Reference	Standard	r_i
↓	Sample (i)	Standard	s_i
$i+1$	Reference	Standard	r_{i+1}
↓	Sample ($i+1$)	Standard	s_{i+1}
$i+2$	Reference	Standard	r_{i+2}
·	·	·	·

of the WLS fibers (see Fig. 15). For this measurement, we prepared a set of standard WLS fibers (typically 60 cm long). The length of the standard fibers was about 30 cm longer than the nominal length, which induces an extra light attenuation. Light from the standard WLS fiber embedded in the sample tile was directly read out with a PMT (H1161GS); there were no clear fibers nor fiber-to-fiber connections. An EM shutter installed between the PMT and the WLS fiber makes an air gap which attenuates the light intensity. Under the given conditions of the measurement, our requirements correspond in this system to the light yield to be more than 12 pes and the variation of the light yield to be less than 2% after subtracting the variations due to non-uniformity of the concentration of the wavelength shifter and the thickness of sample tiles.

The variation of quality of standard fibers was corrected using a reference tile. We monitored the light yield of a standard fiber with the reference tile before and after the measurement with a sample tile. We measured the light yield of sample tiles and the reference tile as shown in Table 6.

Table 5
List of tiles sampled in this test. We sampled 513 tiles in total. Note that a 15° unit in the layers from 1 to 15 (16 to 23) consists of 20 (18) scintillating tiles

Layer no.	No. of units/layer	Tile no. sampled in a unit	No. of tiles
6, 12	8	1, 2, 3, 4, 6, 8, 10, 12, 14, 16, 18, 20	192
23	8	1, 2, 3, 4, 6, 8, 10, 12, 14, 16, 18	88
1–5, 7–11, 13–15	1	1, 2, 3, 4, 6, 8, 10, 12, 14, 16, 18, 20	156
16–22	1	1, 2, 3, 4, 6, 8, 10, 12, 14, 16, 18	77
			total 513 (2.2%)

Each measurement was performed after checking the quality of the standard fiber using the reference tile. We use a ratio

$$R_i \equiv \frac{s_i}{(r_i + r_{i+1})/2} \qquad (4)$$

as a measure of the relative light yield of the sample tile, where $s_i(r_i)$ is the light yield of sample tile i (the reference tile) with a standard fiber. When the light yield of a standard fiber with the reference tile became lower than a given threshold, we replaced the fiber with another. Once we define the absolute light yield using the reference tile with the standard fiber r_0, we can estimate the absolute light yield $s_i^{\rm abs}$ of sample tile i as follows:

$$s_i^{\rm abs} = r_0 \times R_i. \qquad (5)$$

The variation of the light yield of sample tiles was measured to be 3.0%. The measured variation includes (i) the variation of the tile thickness (1.6%), (ii) the variation due to the non-uniformity of the wavelength shifter concentration (1.7%), and (iii) the variation due to the uncertainty of the measurement (1.0%) in addition to the variation of the tile fabrication. By subtracting these numbers from the measured variation one can estimate the variation that comes from the tile fabrication. We summarize the minimum light yield and the light yield variation of the sample tiles in Table 7. These results satisfy our requirement.

4.4. Fiber fabrication

One end of the WLS fiber is mirrored by aluminum sputtering with a cover of MgF_2, and the other end is spliced to a clear fiber by a thermal fusion method. In order to check the quality of mirroring and splicing, we measured light yield of WLS fibers after these fabrication. In this test we required the variation of the light yield should be less than 5% in rms. We also rejected the fibers of which light yield is greater or less than the average light yield by $\pm$ 10%.

Table 7
Summary of the light yield test results after the tile fabrication

	Result	Requirement
Minimum light yield (pes)	15	> 12
Variation (%)	3.0	—
Extracted variation (%)	1.6	< 2

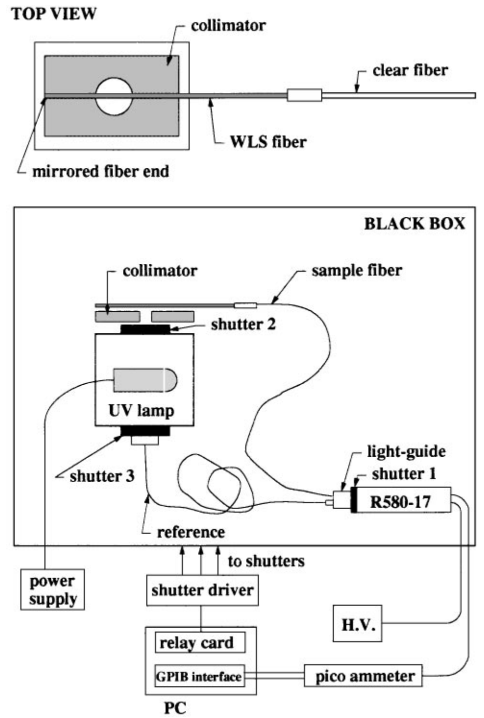


Fig. 17. Experimental setup for the light yield measurement after fiber splicing.

We show the experimental setup in Fig. 17. We use a UV lamp in a small dark box as a light source and a PMT R580-17 (Hamamatsu) as a current readout device. The light from the UV lamp was collimated. We use a reference clear fiber to monitor the light intensity and the PMT gain. The light intensities from the two fibers were measured with a picoamperemeter, and we used a ratio of the measured currents for the sample fiber and the reference fiber as a measure of the relative light intensity of the sample fiber. Fig. 18 shows the distribution of the relative light yield. We obtained the light yield variation of 4.4% in rms. Fibers corresponding to 1.4% of the total had light yield outside the specification and were rejected.

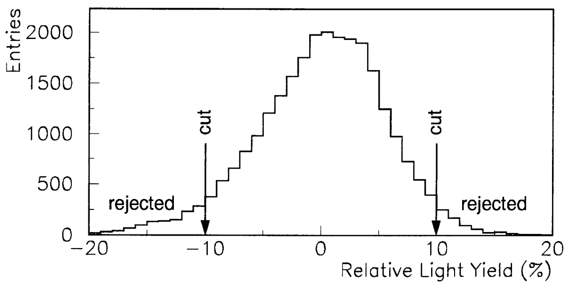


Fig. 18. A distribution of the light yield variation of WLS fibers spliced to clear fibers.

4.5. *Tile/fiber sub-assembly*

We made 15° units with scintillating tiles and WLS fibers spliced to clear fibers that passed our quality tests. In total, 1196 units were produced. As a final quality test, we sampled about 3% of the units and measured the light yield and light leakage to the adjacent tiles within a 15° unit using a β-ray source. We sampled eleven 15° units from the 12th layer and one 15° unit from each of the other layers. The following are our final requirements on the quality for 15° units:

1. light yield of tile/fiber's in 15° units with clear fibers and mass connectors > 3 pes,
2. response variation of tile/fiber's with the same size $< 10\%$ in RMS,
3. response variation of tile/fiber's within a tower $< 30\%$ ($< 10\%$ in RMS), and
4. a total of light leakage from a tile to the adjacent tiles $< 3.5\%$.

The system used in this test is shown in Fig. 19. A 15° unit is mounted on a table. A β-ray source (^{90}Sr) with a lead collimator of 5 mm in diameter and a trigger counter are attached to an arm bar. The source and the trigger counter scan the sample 15° unit, and the light yield of each tile/fiber is automatically measured. As mentioned in Section 2, a 15° unit consists of 18 (or 20) tile/fiber's. We grouped 18 (or 20) readout optical fibers into four and read out with 4 PMTs (Hamamatsu H1161GS). The assignment of the tile/fiber's to the four PMT's is given in Table 8. The uncertainty of the light yield measurement with this system is about 3.0%. We measured the light yield of total light leakage using the four PMT's at once. When we test tile 14 with PMT(2), we also measure the light yield from the tiles 11, 12, 13, 15, and 16, which are all adjacent to the seed tile (tile 14), with the other PMT's, PMT(1), (3), (4). The total light leakage from the seed tile to the adjacent tiles is defined by

$$\mathscr{L}(14)(\%) \equiv \frac{X(11) + X(12) + X(13) + X(15) + X(16)}{X(14)} \times 100,$$

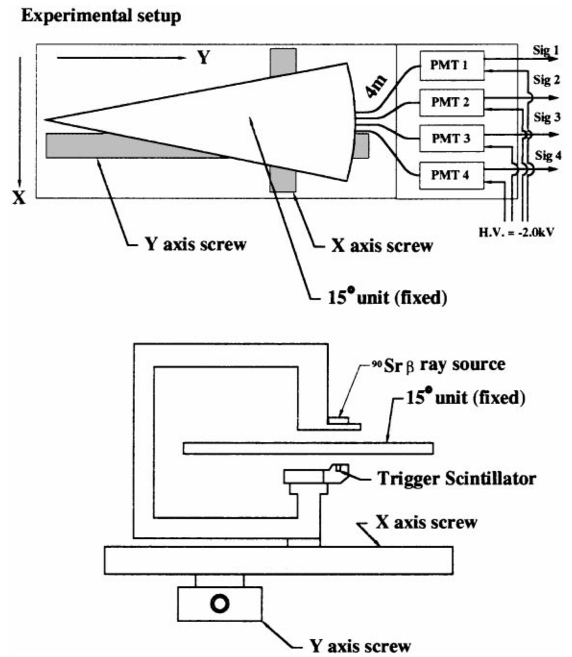


Fig. 19. The automatic scanning system for the light yield measurement of 15° units.

Table 8
The assignment of tiles in a 15° unit to the four PMTs

PMT number	Tile number
PMT (1)	1, 5, 9, 13, 17
PMT (2)	2, 6, 10, 14, 18
PMT (3)	3, 7, 11, 15 (19)
PMT (4)	4, 8, 12, 16 (20)

Table 9
Results of the quality test of 15° units

Measurement	Result	Requirement
Light yield (pes)		
Average	7.7	—
Minimum	5.5	> 3
Variation (%)		
Within a tower	7.9	< 10
With the same sizes	6.4	< 10
Light leakage (%)		
Average	1.1	—
Maximum	2.8	< 3.5

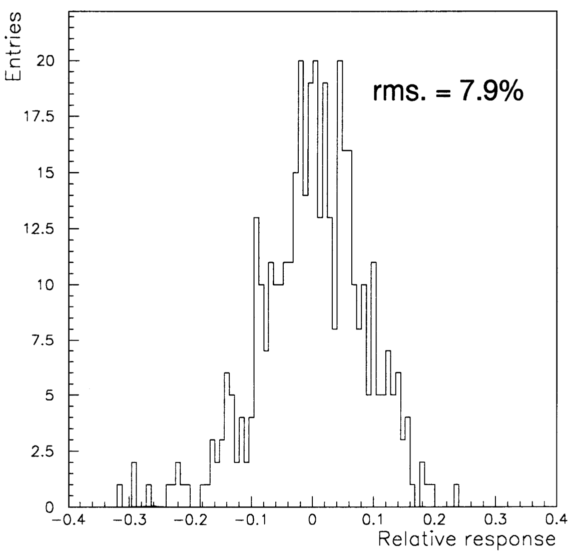


Fig. 20. The response variation within a tower.

where $\mathscr{L}(14)$ is the total light leakage of tile 14 to the adjacent tiles and $X(n)$ is the light yield of tile n.

We summarize the results of these measurements in Table 9. The average light yield of tile/fiber's was measured to be 7.7 pes, and all tile/fiber's satisfied the required light yield larger than 3 pes. Distributions of (i) relative deviation of response of tiles within a tower from the average response and (ii) relative deviation of response of tiles with the same sizes from the average response are shown in

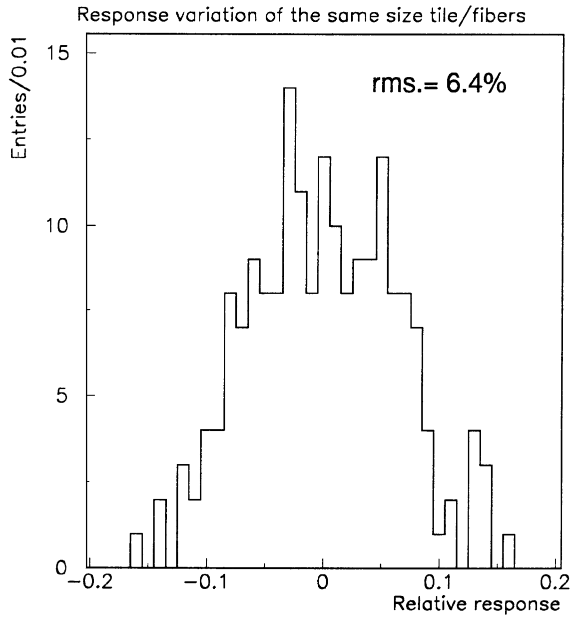


Fig. 21. The response variation of tiles with the same sizes, except for tiles 1, 19, 20.

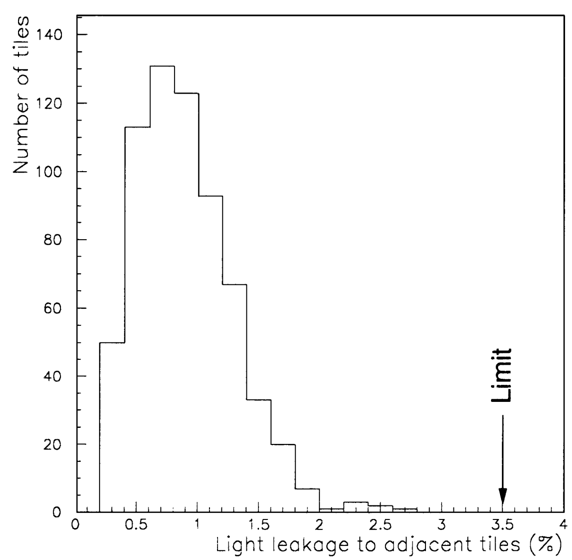


Fig. 22. A distribution of the total light-leakage from a tile to the adjacent tiles within a 15° unit.

Figs. 20 and 21, respectively. Light yield variation of tiles within a tower was measured to be 7.9%. Light yield variation of tiles with the same sizes was measured to be 6.4%. This result is consistent with

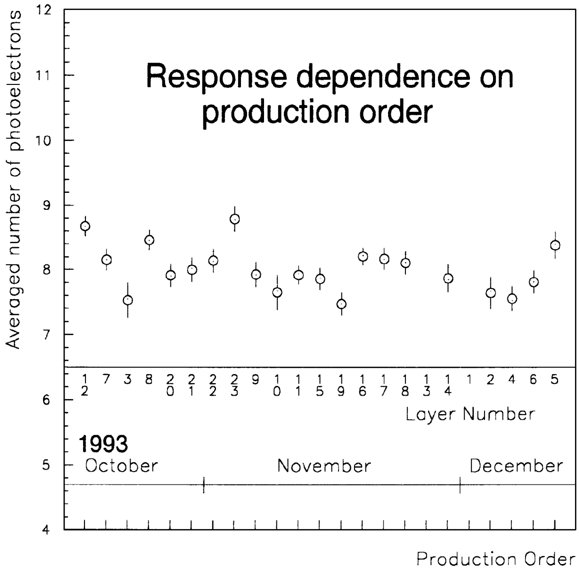


Fig. 23. The average light yield dependence on the production order. No significant dependence was observed.

what we expect from variations of scintillating tiles (2.8%), optical fibers (4.4%), and reproducibility of the measurement (3.0%). These results satisfied our requirements. Shown in Fig. 22 is the distribution of the measured light leakage. We measured the average light leakage to be 1.1%, and all tile/fiber's satisfied our requirement on the light leakage to be less than 3.5%.

We finally show the average light yield of tiles against their production order in Fig. 23. We do not see any significant dependence of light yield on the production order.

5. Conclusion

We performed the quality tests for the CDF plug EM tile/fiber calorimeter at a number of major points in the production. We checked the quality of scintillating tiles and optical fibers to select them satisfying our requirements. We finally sampled 33 of 15° units and checked their quality. We confirmed that all of the sampled units satisfy our requirements. After the production, all of 15° units were tested using cosmic rays in 1995–1996.

References

[1] CDF collaboration, CDF Plug Upgrade Technical Design Report, 1992, p. 14.
[2] CDF collaboration, CDF II Technical Design Report, 1996, p. 9-1.
[3] T. Asakawa et al., Nucl. Instr. and Meth. A 340 (1994) 458.
[4] S. Aota et al., Nucl. Instr. and Meth. A 352 (1995) 557.
[5] S. Kim, Nucl. Instr. and Meth. A 360 (1995) 206.
[6] K. Hara et al., Nucl. Instr. and Meth. A 348 (1994) 139.
[7] K. Hara et al., Nucl. Instr. and Meth. A 373 (1996) 347.