Design of a 2×2 Scintillating Tile Package for the SDC Barrel Electromagnetic Tile/Fiber Calorimeter

K. Hara, S. Kim, H. Maekoba, H. Minato, Y. Miyamoto, I. Nakano, M. Okabe, Y. Seiya,
T. Takano, K. Takikawa and K. Yasuoka

Institute of Physics, University of Tsukuba

Tsukuba-shi, Ibaraki-ken 305, Japan

We describe R&D results on optical properties of a scintillating tile/fiber system for the SDC barrel electromagnetic calorimeter. The tile/fiber system uses a wavelength shifting fiber to readout the signal of a scintillating plate (tile) and a clear fiber to transmit the signal to a phototube. In the SDC calorimeter design, four of tile/fiber systems are grouped as a 2×2 tile package so that the gap width between and the location of the tiles in the absorber slot can be controlled. Optical properties of the tile package such as the light yield, its uniformity, and crosstalks were measured in a testbench with a β-ray source and in a 2-GeV/c π^+ testbeam. The performance as an electromagnetic calorimeter was evaluated by a GEANT simulation using the measured response map. We discuss a method of correction for the calorimeter nonuniformity.

1. Introduction

The Solenoidal Detector Collaboration (SDC) detector [1], designed to be built at the Superconducting Super Collider, employed a scintillating tile/fiber technique [2] for the central calorimeter. A conceptual diagram of the barrel calorimeter is shown in Fig. 1. The calorimeter is longitudinally segmented into the electromagnetic (EM) part and the two hadronic parts (HAC1 and HAC2). At pseudorapidity $\eta = 0$, the EM calorimeter is composed of 30 layers of 4 mm lead interleaved with $\sim$4 mm scintillator tile layers, and HAC1 (HAC2) is composed of 28 (15) layers of 24 mm (54 mm) iron interleaved with 4 mm thick tiles. The signal from the scintillating tile is readout with a wavelength shifting (WLS) fiber embedded in a groove which is machined in the tile. The light re-emitted by the WLS fiber is then transported to a phototube located behind the calorimeter through an optical clear fiber. With such a tile/fiber technique, finely segmented projective tower geometry can be constructed. Also, the number of longitudinal segments is unrestricted; the same technique can be used for the preshower and shower-max detectors. Since the signals are extracted through thin fibers, the calorimeter dead space can be reduced. Fast response of scintillator is utilized in this readout scheme.

The wedge shape barrel calorimeter module covers an $\eta - \phi$ range of $0 \leq \eta \leq 1.4$ and $\Delta\phi = 0.2$. The EM lead absorber structure is designed to be fabricated by casting. The slot size for the tile/fiber systems is $\Delta\eta = 0.1$ and $\Delta\phi = 0.2$. For the designed hadronic tower size $\Delta\eta = \Delta\phi = 0.1$, the tile/fiber systems are inserted into the slots from either side of the wedge and the fibers are extracted in the ϕ gap (space between the wedge modules). The EM tower size is, on the other hand, $\Delta\eta = \Delta\phi = 0.05$. In order to cope with the absorber slot size, 2×2 EM tiles are grouped into a package so that the gap between the tiles and positioning of the tiles are well controlled. Packaging tiles can also simplify the procedure of assembling the tiles into the absorber slots.

We describe the design and the performance measurements of the 2×2 EM tile package. The light yield, its uniformity, and the crosstalk were measured using penetrating β-rays and in a 2-GeV/c π^+ testbeam. The measurements include a fiber bending test, and a test of the pressure effect on the light yield, which were obtained in the early stage of the R&D. With the present design of the tile/fiber system, the response was measured to be approximately 13% high near the tile edge. The performance as a calorimeter was evaluated using a GEANT simulation where the measured tile/fiber nonuniformity was used. The requirement to the energy resolution is $15\%/\sqrt{\mathrm{E}} \oplus 1\%$. In order to keep the overall constant term to be less than 1%, we require that the contribution from the lateral calorimeter nonuniformity should be less than 0.5% [1]. The evaluated calorimeter response nonuniformity does not fulfill the requirement. Since the nonuniformity originates in the optics of the tile/fiber system and is localized near the tile edges, it could be corrected for using a pre-measured response map and the incident point reconstructed from the energy deposit asymmetry in the neighboring towers. We discuss a correction method and evaluate the corrected calorimeter response.

2. Design of the tile package

2.1 Tile/fiber assembly and tile package

A diagram of the tile package consisting of 2×2 EM tiles is shown in Fig. 2. The size of the tile was approximately 11 cm in ϕ and 11–23 cm in η depending on the location. We used Kuraray SCSN38 scintillator and 0.83 mmϕ multiclad WLS fiber with a Y11 concentration of 200 ppm. The WLS fiber was embedded into a peripheric groove machined in the scintillating tile. The groove makes a turn by 90° at the tile corners at a radius of 3 cm. This radius was determined from a response uniformity measurement and a fiber bending test, as described in Section 2.3. The distance of the groove from the tile edge and the groove depth were optimized using a pion testbeam. In order to keep the fiber in position, the groove had a key-hole shape cross section [3,4] with a 0.8 mm wide slit and a 1.2 mm diameter hole (see the enlarged diagram (B)). Such a groove was machined in multiple steps by using an endmill to cut to depth and then by using a ball-end mill.

The four sides of the tile were sprayed with white reflective paint to a thickness of 30–60 μm. In selecting the white paint, we have tested reflectivity and adhesiveness of three products, Bicron BC620, Nuclear Enterprise NE560, and Nippon Paint O-de Coat. Since there were no difference observed, we selected O-de Coat for application experience to scintillator over many years. O-de Coat is TiO_2 based emulsion paint. The four surfaces were, then, wrapped in a white PET (polyethylene terephtarate) sheet. Use of a thin, 50 μm, PET sheet was essential in reducing the gap between tiles. Comparison with other reflective sheets is discussed in Section 2.4.

To form a tile package, four such tiles were positioned to a top plate, a white PMMA board of 1.5 mm thickness, by use of $\sim$3 mm long 2 mmϕ scintillating pins. The measurement on optical properties is described in Section 2.5. Four holes were machined at the tile corners to 1.3 mm depth, to which the pins were inserted. The pins were, then, pushed through the holes which were machined in the top plate. The head of the pins were melt and flattened from the other side of the top plate. In this way, the tiles can be positioned to the top plate at a machining accuracy of typically 50–100μm. The four readout fibers were extracted to the same package side where the ϕ-gap between the calorimeter modules located, as shown in the figure, and, then bent by 90° towards the phototubes. There were grooves machined on the top plate facing to the tiles, through which the fibers were extracted. In this design, the fibers were mechanically protected against possible pressure from the absorber plates, and insertion and replacement of fibers were made possible without taking the package out of the slot. Indeed, extracting a certain package out of the slot would be complicated after other packages were set in position.

The WLS fiber was thermally spliced to Kuraray multiclad clear fiber of 0.83 mm in diameter. Since the splice used a 0.2 mm thick tube for fiber axis alignment and mechanical support [5], the guide groove in the top plate had a cross section shown in the figure (D). The groove near the tile entry had a slope to guide the fiber into the tile groove. The other end of the WLS fiber was mirrored by aluminum sputtering. Since the mirrored end might be damaged during insertion in this design, we tested rigidity of the mirror. The sputtering procedure and the result of this test are described in Section 2.6.

The four surfaces of the tile was wrapped with a PET sheet, as mentioned before. This was to simplify the wrapping procedure. A double-coated tape was used at the overlap of the PET sheet. The direction of the wrapping was alternated among the four tiles in order to reduce the crosstalk. The entire package was wrapped by another PET sheet to prevent scratches when it is inserted into the slot. The width of the package was tested to be $\sim$0.2 mm smaller than the slot width so that the package was inserted smoothly. More importantly, the wrapping direction of this PET sheet had to be same as the direction of insertion. The gap space needed in height was even smaller, and $\sim$0.1 mm was found to be adequate. Taking into account the tolerance of the tile thickness, $\pm$0.2 mm, of the top plate, $1.5\ ^{+0.1}_{-0.05}$ mm, and the thickness of the PET sheets including the overlaps and the double-coated tape, the nominal tile thickness should be 3.6 mm for a nominal slot gap of 6 mm where a tolerance of 0.2 mm is given additionally.

2.2 Light yield

In our testbench measurements, the light yield was evaluated by measuring the charge induced by penetrating ^{90}Sr β-rays which were triggered by a scintillation counter set underneath the sample. The light yield was defined as the number of photoelectrons (PEs) emitted from the photocathode of a green-extended phototube, Hamamatsu H1161G. The quantum efficiency at 520 nm (Y11 emission peak) was typically 18%. The gain of the phototube was evaluated from the charge corresponding to the single photoelectron. The single photoelectron distribution was measured by reducing the light with a neutral density filter to approximately 0.1 PEs so that the contribution of $\geq$ 2 PEs was negligible. The peak charge of the so obtained distribution was used to define the single photoelectron charge. The number of PEs of the sample was given as the ratio of the mean charge to the single PE charge thus determined. More detailed procedure can be found in [6,7].

Fig. 3 shows the light yields of 4 mm thick SCSN38 tiles readout with 1 mmϕ WLS fibers. The tile was rectangular with the longer (η) side length varying from 125 mm to 225 mm, while the shorter side length was fixed to 105 mm. The data are compared for the three fiber configurations, with and without a 3 m clear fiber spliced, and without the mirror at the Y11 fiber end. Since this measurement was made in an early stage of the R&D, we used a thicker WLS fiber. The number of PEs is greater than 7 with the mirror and with a 3 m clear fiber spliced. The mirror increases the light yield by 40% for the longest tile and by 55% for the shortest tile.

We measured that the light yield changes almost linearly with the WLS fiber diameter in the range from 0.75 to 1.0 mmϕ. With 0.83 mmϕ WLS fibers, we measured the light yield for tiles of $125 \times 105 \times 4$ mm^3 to be approximately 6 PEs. The light yield is also proportional to the tile thickness [3]. We expect to get a light yield of about 5.5 PEs/mip for 3.6 mm thick tile/fiber systems readout with 0.83 mmϕ WLS fibers. We evaluated the systematic uncertainty in the light yield measurement to be less than 10%. The systematic uncertainty includes the uncertainty in the single PE charge determination and that in the correction for the path length traversed by β-rays, each of which contributes by ~5% to the light yield measurement. The light yield of the tile/fiber assembly, therefore, fulfills the requirement that the light yield be greater than 4 PEs/mip.

2.3 Fiber bending test

In the fiber bending test we first measured the initial degradation and then the change with time in the light transmission. In the first test (Fig. 4), the sample WLS fiber was bent by 360° and the light transmission was measured by changing the radius of the circle. The part near the WLS fiber end was excited by a blue LED with an emission peak at 470 nm, and the amount of light emerging from the other end was measured with a phototube. We tested Kuraray S-type [8] fibers with diameters of 0.75, 0.83 and 1.0 mm. For all the samples the light transmission started to drop at a bending radius of ~10 mm and decreased substantially below 7 mm.

In the second test (Fig. 5), 3 m long fibers were coiled at fixed radii of 5, 10, 20, and 40 mm and the light yield change was traced for three months. The light transmission T_1 is plotted in the figure, where the actual light transmission T_{meas} measured in the test was $T_{meas} = (T_1)^n$, n being the number of turns. The transmission T_1 at a radius $\geq$ 20 mm are stable to 0.05%, but that at 5 and 10 mm showed a decrease of 0.35% and 0.15%, respectively. Although the magnitude is small and the transmission becomes stable in ~300 hrs even at these small radii, the change might develop further in different conditions. Therefore, we decided conservatively to set the radius larger than ~3 cm. At a larger radius, on the other hand, the response near the tile corner outside the fiber groove was measured to drop substantially and the uniformity was degraded. From these considerations, we set the radius to 3 cm.

2.4 Wrapping material

Comparison of several wrapping materials in terms of the tile/fiber light yield is discussed in [4], where PET and fiber paper (DuPont TYVEK) are reported to produce the largest light yield. We tested various reflective sheets in terms of the light yield variation under pressure. This study was initiated when the SDC calorimeter group considered an option of stacking and tying together the tiles and lead absorber plates as an alternative to the lead casting scheme. Some pressure is foreseen in the lead casting as well due to possible deflection of absorber plates.

A sample tile/fiber assembly of 11 cm square was pressed uniformly by an air cylinder. The pressure was uniform over the tile face to 15%, which was confirmed with a sheet of Prescale of Fuji Film Co. Ltd. This sheet turns red when pressurized and the tints provide an absolute measure of the pressure, which agreed with the pressure calculated from the applied air pressure. The sample tile/fiber assembly was set between a pair of aluminum blocks, where slits and shallow grooves are machined so that a trigger scintillation counter and a β source were set in the grooves and that β rays passed through the slits.

The results are shown in Fig. 6. The tested reflectors were PET, printer paper (200 μm), fiber paper (150 μm), and aluminized mylar (20 μm). The light yields are normalized at zero pressure. A typical size of the measurement uncertainty is 6%, which was derived from the reproducibility. For all the reflectors, the light yield decreased monotonically with the pressure. If the pressure was localized, on the other hand, we measured essentially no decrease up to 12 atms. This decrease when pressurized uniformly could be attributed to loss of the air between the tile and the reflector, which reduces the probability of total reflection at the scintillator surface and, in turn, increases the probability of reflection by the reflector itself. Among these samples, PET and printer paper showed the smallest reduction in the light yield. With a PET sheet the light yield at no pressure was measured to be higher by 20% than that with printer paper. PET is chemically stable, and was also measured not to deteriorate after irradiation of up to 10 Mrad. From these measurement results we selected PET of 50 μm thickness.

We measured the crosstalk in the tile packages by scanning with a ^{90}Sr source. The crosstalk from an adjacent tile was measured to be 0.4%, almost independent of the source position. The crosstalk from the tile at the diagonal position was 0.05%. The amount of the cross crosstalks is small enough for the SDC EM calorimeter.

2.5 Response on the scintillating pin

The top plate was designed to be slightly (100 μm) oversized than the overall tile size so that the top plate defines the tile position in the slot. The position of the tiles with respect to the top plate was determined by the scintillating pins. Scintillating pins were used for the purpose of recovering the response drop caused by pins. The region near the scintillating pin was mapped at every 0.5×0.5 mm^2 mesh point. In order to see the effects excluding the nonuniformity due to other causes, a scintillating pin was positioned near the tile center. The uniformity results were compared with a PMMA pin of the same size.

Fig. 7 shows a slice of the map along the line that passes on the pin center. The response is normalized at the tile center. The collimator for β rays was 1 mmϕ. The recovery of the light yield due to the scintillating pin is clearly seen. The maximum response nonuniformity is 6% for the scintillating pin, while the response is low by 12% at the center of the PMMA pin. We evaluated the impact of this nonuniformity on the electron energy measurement.

The response to 100 GeV electrons was calculated with a GEANT [9] simulation assuming that the uniformity map was 100% coherent in the calorimeter depth. The simulation results are also plotted in the figures. The maximum nonuniformity is 0.7% for the scintillating pin, and 2.1% for the PMMA pin. Since the effect is localized and small, the nonuniformity seen for the scintillating pin is acceptable. The effect could be reduced further by staggering the pin location in depth.

2.6 Fiber end mirroring

In the present design, the signal is readout from one end of the WLS fiber and the other end is mirrored, which increases the tile/fiber light yield by nearly 50%. Since readouting the both fiber ends doubles the number of splices, the number of clear fibers, and the space needed for fiber routing, we chose the present readout scheme.

In order to ensure hardness of the mirror, we employed a method based on aluminum sputtering. The fiber ends were prepared, at first, by cutting them at a right angle with a diamond flying cutter, and then they were exposed in a vapor of $CHCl_3$ for less than a second prior to sputtering. The thickness of aluminum layer was 80 nm. In order to enhance the mechanical hardness further, MgF_2 was evaporated right after the sputtering in the same vacuum chamber.

The reflectivity of the mirror was evaluated by measuring the induced currents from the other end when a 2 cm long part near the mirrored end was coupled to a small scintillator block to which a β source was fixed. The reflectivity was defined as an excess of the current with mirror with respect to the case where the mirror was trimmed off and the end was blackened. We achieved a reflectivity of $89 \pm 2\%$. The reflectivity was found to be quite dependent on the fiber end preparation, and such a high and uniform reflectivity was made possible by the chemical polishing process using $CHCl_3$.

In the present design of the top plate, the fiber is required to be inserted from the mirrored end. We repeated multiple times of insertions and measured if the light yield was degraded. It was found that the friction at insertion and the light yield degradation were correlated, and the friction was made smaller by increasing the groove width in the tile. For a groove width of 1.2 mm, we measured essentially no degradation for 10 times of insertions we tested.

3. Uniformity measurement in a testbeam

3.1 Testbeam setup

The light yield uniformity was measured in a 2-GeV/c π^+ beam at the KEK proton synchrotron. We tested eight packages with various groove depths of 1.7, 1.9, 2.1, and 2.4 mm for the fiber path 2 mm from the tile edge, and of 1.5, 1.9, 2.1 and 2.4 mm for the 5 mm fiber path. The size of the sample packages was 21×25 cm^2. There were four sets of drift chambers set along the beam line as shown in Fig. 8. The eight samples were stacked and placed between the second and the third chambers. The clear fibers 3 m long were extracted through a light-shielded tube to a phototube box. Each of the clear fibers was coupled to an H1161G phototube through a light mixer, a Lucite block 2 cm square and 5 cm long. We used a source calibration system in order to monitor the gain of the phototubes by measuring single photoelectron distributions between the beam spills. The calibration system consisted of a scintillating tile with multiple straight grooves where 32 Y11 fibers were coupled. They were distributed to the phototubes through the light mixers. Throughout the beamtest measurement, two sets of 15° units and two preshower units for the CDF plug upgrade calorimeter [4] were located in front of the tile packages. These units had a mass equivalent to 38 mm thick plastics in total.

Each of the drift chambers consisted of two single-sense-wire drift cells assembled perpendicularly to each other. The sense wire was positioned asymmetrically in the drift cell with a maximum drift distance in the wider side being 72 mm. Only the wider side was used in order to eliminate the left-right ambiguity. The second and fourth chambers were rotated 180° with respect to the others to allow inter-calibration of the drift velocity. The calibration data for the drift time were obtained using a trigger S1·S6 (see Fig. 8). The accuracy of reconstructed track position was evaluated from the response shape near the tile edge, and was 0.5 mm in sigma.

The signals from 32 phototubes and eight beam chambers were readout by CAMAC ADCs and TDCs, respectively. The beam trigger, S1·S2·S3·S4·S5·S6, and the source trigger, coincidence of the two phototubes in the calibration system, were alternately turned on using the beam spill gate. The light yield was calculated as the ratio of the mean charge obtained by the beam trigger to the single photoelectron peak by the source trigger. We used two sizes of S4 counters in the uniformity measurement. A strip counter 1×7 cm^2 was used to take data across the tile package, and a square counter 7×7 cm^2 was used to map the response around the center of the package where the corners of the four tiles contact. We call these two triggers LINE and SQUARE, respectively.

3.2 Light yield uniformity across the package

The light yield uniformity was measured across the package on the median line of the upper two tiles. A typical response shape is plotted in Fig. 9, where the outputs from the two adjacent tiles are summed after each response is normalized at the tile center. The sample had the fiber path 2 mm from the tile edge and 2.1 mm groove depth. Since the

LINE trigger (and beam chambers) covered only 7 cm, the samples were set on a moveable table and moved horizontally to cover the full width of the packages. The nonuniformity is measured to be small in the wide area of the package except for regions near the tile edges. After subtracting the statistical error, the rms nonuniformity in a central region excluding the peripheral areas of 30 mm from the tile edges is 2.0%, independent of the groove depth and of the fiber path. Since the nonuniformity is at random, the rms value is dependent on the bin size. The rms nonuniformity of 2.0% evaluated for a 1 mm bin size is reduced to 1.0% for a 5 mm bin size.

Detailed distribution near the boundary of the two tiles is also shown in the figure. The response is low at the boundary gap and on the fiber, reflecting a thin average thickness of scintillator. The response is high in a region approximately 10-15 mm from the edge. The size of this region was measured to be independent to the fiber path and to the groove depth. In Fig. 10 we plotted the maximum response (peak nonuniformity) measured near the edge and the response on the fiber as a function of the groove depth. Each of the plotted values is the average of the four data values for each of the tile packages. The data points lie nearly on the same curve for the two fiber paths. The peak nonuniformity is about 13% and does not seem to depend on the groove depth. The response on the fiber, on the other hand, decreases gradually with the groove depth. From all the samples we derived that the rms variation of the peak nonuniformity was about 2%. We take this rms value as a measure of the individual difference of the peak nonuniformity, and assume that the same level of variation is expected for the packages in mass production.

3.3 Light yield uniformity near the package center

The response near the package center where the corners of the four tiles contact was measured using the SQUARE trigger. For the 2 mm fiber path, the response map is shown in Fig. 11 with a mesh size of 3 $\times$3 mm^2. The response is normalized by that at the tile center. The results for the 5 mm fiber path are shown in Fig. 12. Since the main objective of this measurement is to evaluate the response shape near the tile corner, and since the nonuniformity is barely dependent on the groove depth (except for the region just on the fiber), the maps with different groove depths are averaged in order to increase statistical significance. The histogram in each of the figures shows the distribution of the response values measured at the 100 mesh points. The response at the point where the four tiles contact, (0,0) in the figures, is not different between the two fiber paths 2 mm and 5 mm, and it is 70% and 67%, respectively. The main difference between the two fiber paths is the response in the corner region outside the groove. Because the response recovery is moderate for the 5 mm fiber path, the histogram shows a wide spread, whereas it shows a narrower peak at around 1.05 for the 2 mm fiber path.

4. Performance simulation as an EM calorimeter

4.1 Calorimeter nonuniformity at the tile center

In Section 3.2 the random nonuniformity of 1.0% is evaluated for a 5 mm bin size in the central area of the tiles excluding the regions 30 mm from the tile edges. Using GEANT we have simulated the effect of this nonuniformity on the calorimeter energy resolution assuming that the nonuniformity is not correlated in the calorimeter depth. In this simulation the tile/fiber response averaged over the lateral shower spread is the meaningful quantity, since even a large nonuniformity would be smeared if the nonuniformity structure is fine. When we simulate the calorimeter response at a certain incident point, the response is set to be uniform within a tile while the response of different tiles is varied according to a Gaussian function with a given sigma. When we change the incident point, another set of response values is given to the tiles with the same sigma. We evaluated the resolution degradation at 1000 incident points and derived the rms spread of the resolution degradation which refers to the degradation due to the random nonuniformity. The simulation results are shown in Fig. 13. The induced resolution degradation is proportional to the random nonuniformity value independent of the electron energy from 10 GeV to 400 GeV we simulated.

The spread of the electron shower is typically 5 mm (FWHM). Hence the random nonuniformity 1.0% evaluated for a 5 mm bin size induces a calorimeter response nonuniformity of approximately 0.2% according to Fig. 13.

4.2 Calorimeter response near the tile edge

The nonuniformity map near the tile edge was used in the simulation assuming, in this case, that the response is 100% coherent in the calorimeter depth. We simulated the calorimeter response using mainly electrons of 100 GeV and the energy dependence was studied by comparing the results with those for 10 GeV electrons.

The calorimeter response evaluated based on the tile response shown in Fig. 9 is plotted in Fig. 14. The response is normalized by that at the tile center. The calorimeter response is high by approximately 5% at the points 8 mm from the tile edge, and the nonuniformity is larger than 1% in the region about ± 20 mm from the edge. In a region 30 mm from the tile edge, the mean calorimeter response is shifted by $+2.6\%$, and the rms deviation from the mean is 1.4%. The rms deviation of the calorimeter response with respect to the response at the tile center is a quadrature sum of these two values, 3.0%.

The response shape in the figure is asymmetric, and there is a difference of 1.2% in the calorimeter response at the two peaks. This is due to the fact that the slight difference in the response shapes of the two tiles shown in Fig. 9 is retained in the present assumption of 100% coherence in the depth. In the actual case, tiles with various response shapes are stacked randomly, and this effect should be diluted. Since the peak nonuniformity is measured to vary from tile to tile with an rms of 2%, the difference in the peak calorimeter response is evaluated to be about 0.2% from a study similar to that described in Section 4.1.

There are other causes that could affect the calorimeter response shape. First, electrons produced in pp collisions enter the calorimeter obliquely when interactions occur away from the detector center. In Fig. 14 we plot the response shapes when electrons are incident with $\theta = 5^\circ$ and 10°, where θ is the incident angle with respect to the normal line to the calorimeter face. An angle of $\theta = 5^\circ$ corresponds to an offset of 18 cm in the interaction point for a calorimeter located at a radius of 2.1 m. The response near the tile boundary deviates by 1% at most for $\theta = 5^\circ$. In this case the rms spread of the response in the region 30 mm from the edge is reduced from 3.0% to 2.7%.

Second, the boundary gap width can vary with a manufacturing precision. By use of scintillating pins, the gap width can be controlled to 0.4 mm with a precision of approximately 0.1 mm. We therefore evaluated the variation of the response for an extreme case where the gap widths of all the packages were widened by 0.2 mm. Since a 0.2 mm wider gap effectively reduces the tile response on the boundary by 20% if the response is measured in a 1 mm bin, the calorimeter response was evaluated for a tile response so modified. The response was found to decrease by 1.9% locally on the boundary in this extreme case.

Third, the boundary location may not be projective in depth. The slot size is designed to be wider by 0.3 mm than the package size. The variation of the response was estimated to be negligible (0.4%) even for an extreme case where the location of the boundary was staggered in depth by ± 0.5 mm.

In summary, the rms spread of the calorimeter response in the region within 30 mm from the edge is 3.0%. It changes to 2.7% for electrons injected at an angle of 5°. Effects due to finite fabrication precision are small and localized, and negligible if averaged by the area.

4.3 Calorimeter response at the corner

The calorimeter nonuniformity at the tile corner was evaluated similarly. In the calculation the two-dimensional response map shown in Fig. 11 was used in a GEANT simulation. The resulting calorimeter map for the 2 mm fiber path is plotted in Fig. 15 together with a histogram for the 100 mapped points. The calorimeter nonuniformity is worse for the 5 mm fiber path. Comparing to the tile nonuniformity, the calorimeter nonuniformity at (0,0) is reduced, but it is still low by 11%. In this 30×30 mm^2 region at the corner the rms spread of the calorimeter response is 3.4%, and the average response is shifted by +2.3% with respect to that in the central region.

4.4 Response correction using energy deposit asymmetry

The overall calorimeter response nonuniformity can be evaluated from the numbers evaluated so far. The relevant values are summarized in Table 1 for the tile response and for the calorimeter response simulated for 10 and 100 GeV electrons. In the table, the mean and the rms variation are separately given. To calculate the nonuniformity averaged over the package surface, we average the means in the three regions weighting by the areas, and then calculate the rms variation to that new mean. For 100 GeV electrons incident at 0°, for example, the average response is 1.023 with respect to that at the tile center, and the rms variation is 1.9%. The energy dependence and angle dependence are small. The rms variation is in a range from 1.7% to 2.1% for 10 and 100 GeV electrons incident at $0°$ and $5°$ we evaluated. These numbers refer to the contribution to the energy resolution degradation due to the lateral calorimeter nonuniformity, and exceed the requirement of 0.5%, if no response correction is applied.

The calorimeter response can be corrected once the incident point is calculated. Since the nonuniformity shape is not sensitive to the manufacturing precision and hence is similar in different towers, the correction procedure would be simple. The fact that the nonuniformity is localized near the boundary gap allows us to calculate the incident point from the energy sharing between towers without relying on tracking information. Here, we used a quantity $A_\eta = (E_R - E_L)/(E_R + E_L)$ to reconstruct the incident point, where E_R and E_L refer to the energy depositions in the two neighboring towers in η.

In the calculation the tile response was assumed to be given by that shown in Fig. 9 and 100% coherent in depth. Incident points about 15 mm from the boundary seem possible to be reconstructed by using A_η. Outside this region A_η approaches to its asymptotic value of ± 1 and its sensitivity to the incident point is degraded. The calorimeter nonuniformity on the boundary such as the dip and the bumps shown in Fig. 14 are fully correctable by using A_η. The corrected calorimeter response showed a mean shifted by +0.09% from the response at the tile center and an rms spread of 0.26%. The incident point at the tile corner can also be reconstructed similarly by using A_η and A_ϕ, where A_ϕ is the asymmetry in the energy depositions in the two neighboring tower in ϕ. The residual response had a +0.02% shift in the mean and a 0.16% rms spread. Averaging these numbers and 0.2% in the central region, we evaluate the contribution to the energy resolution degradation after the correction to be 0.22%.

The mean shift and rms spread of the corrected response are summarized in Table 2. After the correction described above the energy resolution degradation was made small because, in part, the reference response function with which the nonuniformity was corrected for was exactly the same as the calorimeter nonuniformity to be corrected for. The deviation from this reference response function was already discussed in Section 4.2. We recall that the effects due to finite manufacturing precision are small (less than 0.2% locally) and the largest contribution is due to the angle of incident electrons. We studied the effects of the angle for 10 and 100 GeV electrons. The reference calorimeter response shape and the asymmetry-to-position function were calculated for 100 GeV electrons incident at $\theta = 0°$. The same function was used for A_η and A_ϕ asymmetry needed for correction at the corner. The numbers in the table are values so obtained using the single reference calorimeter shape and the single asymmetry-to-position function.

The rms nonuniformity was 0.29% at 10 GeV and $\theta = 0°$. The degradation due to the angle is substantial and the rms for $\theta = 5°$ is 0.51% at 10 GeV and 0.57% at 100 GeV. In view of the required resolution degradation contribution of 0.5% due to the lateral calorimeter nonuniformity, the corrected response fulfills the requirement if the incident angle is smaller than $\sim 5°$. If the offline reconstruction can inform the incident angle, the present tile/fiber calorimeter can also perform as required to the particles with larger angles.

4. Summary

We have carried out R&D on a scintillating tile/fiber system and on a 2×2 tile package for the purpose of applying them to the SDC EM calorimeter. The light yield was about 6 photoelectrons/mip for the tile/fiber system that used 4 mm thick SCSN38 scintillator and a 0.83 mmϕ Y11 fiber spliced to a 3 m clear fiber. The response uniformity was measured in a π^+ testbeam. The response was measured to become high towards the tile edges. The maximum nonuniformity was about 13%, which is not dependent on the groove depth nor on the distance of the fiber path 2 or 5 mm from the edge. The response at the package center where the corners of the four tiles contact is low by $\sim$30%, and the response around has a narrower spread for the 2 mm fiber path than for the 5 mm fiber path.

The performance as an EM calorimeter was evaluated using a GEANT simulation where the measured tile package response map was used. We evaluated the energy resolution degradation due to lateral calorimeter nonuniformity to be 1.7–2.1% for a typical EM tile of 10×12 cm^2 without applying any correction. Since the response nonuniformity was found not to depend on the finite fabrication precision such as the variations of the position and the width of the boundary and since the nonuniformity is localized near the tower boundaries, we discussed a response correction method where we used a reference response function and the incident point reconstructed from the energy asymmetry in the neighboring towers. The residual contribution to the resolution degradation is 0.22% for 100 GeV electrons incident at 0°. It changes to 0.29% for 10 GeV electrons, and to 0.51-0.57% for 10-100 GeV electrons incident at 5°.

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Figure Captions

Fig. 1. Conceptual diagram of the SDC barrel calorimeter wedge module ($\Delta\phi = 0.2$) and the tile/fiber systems ($\Delta\phi = 0.1$).

Fig. 2. Top and side views of the 2×2 tile package (dimensions in mm). The peripheric path in each of the tiles is the groove for the WLS fiber. The WLS fiber is spliced to a clear fiber, which is extracted to the η side through the groove shown as the thick curve. Enlarged diagrams are (A) the scintillating pin that fixes the tile to the top plate, (B) the groove shape machined in the tile, (C) the grooves in the top plate and in the tile near the tile entry, and (D) the groove shape machined in the top plate.

Fig. 3. Light yield of tile/fiber assemblies as a function of the longer side length of the tile. The shorter side is 10.5 cm. SCSN38 of 4 mm thickness and 1 mmϕ Y11 fiber of 60 cm length are used. Compared are the data (crosses) without mirror, and (diamonds) without a 3 m clear fiber spliced.

Fig. 4. Light transmission as a function of the bending radius of WLS fibers. The light transmission is normalized by that at a radius of 6 cm. The inset shows details of the data where changes occurred.

Fig. 5. Light transmission per turn as a function of time measured for four different radii of 0.5 to 4 cm.

Fig. 6. Light yield as a function of the pressure on the tile. Data are compared for various

reflective sheets. The uncertainty in the measurement is typically 0.06.

Fig. 7. Response around the scintillating pin (circles) in comparison with that around the PMMA pin (crosses). The curves show calorimeter response shapes simulated for 100 GeV electrons.

Fig. 8. Experimental setup at the KEK testbeam line. Numbers in the parentheses are dimensions of the trigger counters in cm. The inset is a phototube calibration system.

Fig. 9. (top) Typical response across the package. The boundary is located at zero. Data points with poor statistical errors are excluded. The distance of the fiber is 2 mm from the edge and the groove depth 2.1 mm. (above) Enlargement of the response near the boundary.

Fig. 10. The maximum response ("peak nonuniformity") and the response on the fiber plotted against the fiber depth. Data are shown for two fiber paths 2 mm (open circles) and 5 mm (filled circles) from the tile edge.

Fig. 11. Response map (3×3 mm^2 mesh size) around the tile corner. The three tiles at neighbor are contacting with this tile at (0,0). The map is for the fiber path 2 mm from the tile edge. Histogram is for the 100 measured points.

Fig. 12. Same as Fig. 11, but for the fiber path 5 mm from the tile edge.

Fig. 13. Monte Carlo simulation of the induced energy resolution degradation as a function of the lateral nonuniformity. The nonuniformity is assumed to be not correlated in depth.

Fig. 14. Monte Carlo simulation of the calorimeter response near the boundary. Electrons of 100 GeV are incident at angles of 0°, 5° and 10° with respect to the normal line to the calorimeter face. The uniformity data shown in Fig. 9 is used assuming that the response is 100% coherent in depth.

Fig. 15. Monte Carlo simulation of the calorimeter response at the corner. The map shown in Fig. 11 is used assuming that the shape is 100% coherent in depth.

Table 1

Summary of nonuniformity values for the tile response and simulated calorimeter response. The values are separately given for the three regions, (edge) within 30 mm from the tile edge, (corner) 30 mm $\times$ 30 mm at the tile corner, and (center) the rest. The two values in each column are the mean response normalized by that at the center, and the rms spread in percentage. The values for the calorimeter response are given for the two incident angles 0° and 5°.

Region	Tile	Calorimeter response			
		100 GeV		10 GeV	
		0°	5°	0°	5°
Center	1.000 : 1.0%	1.000 : 0.2%	1.000 : 0.2%	1.000 : 0.2%	1.000 : 0.2%
Edge	1.029 : 3.4%	1.026 : 1.4%	1.025 : 1.1%	1.026 : 1.3%	1.027 : 1.2%
Corner	1.020 : 7.5%	1.033 : 2.3%	1.032 : 2.1%	1.023 : 3.2%	1.029 : 2.4%
Average	1.021 : 4.5%	1.023 : 1.9%	1.022 : 1.7%	1.020 : 2.1%	1.022 : 1.8%

Table 2

Summary of residual nonuniformity values for the calorimeter response corrected by the method described in the text. The reference calorimeter response used in the method is that for 100 GeV electrons incident at 0°. In calculating the average, 0.2% residual nonuniformity was assumed for the central area.

Region	100 GeV		10 GeV	
	0°	5°	0°	5°
Edge	1.0009 : 0.26%	1.0006 : 0.61%	1.0001 : 0.29%	1.0017 : 0.53%
Corner	1.0002 : 0.16%	1.0016 : 0.69%	1.0020 : 0.32%	1.0008 : 0.66%
Average	1.0005 : 0.22%	1.0008 : 0.57%	1.0007 : 0.29%	1.0011 : 0.51%