Abstract

We present a novel geometry of scintillator tiles developed for fiberless coupling to silicon photomultipliers (SiPMs) for applications in highly granular calorimeters. A high degree of uniformity of the tile response over the full active area was achieved by a drilled slit at the coupling position of the photon sensor with 2 mm, 4 mm and 5.5 mm in height, width and depth. Detailed measurements of the response to penetrating electrons were performed for tiles with a lateral size of 3 × 3 cm² and thicknesses of 5 mm and 3 mm.

Key words: Calorimeter, Scintillator, SiPM, MPPC, Direct Coupling

1. Introduction

The physics at a future high-energy linear e⁺e⁻ collider imposes stringent requirements on the detector performance. The detailed study of physics beyond the Standard Model as well as precision measurements of Standard Model processes demand excellent reconstruction of multi-jet final states with missing transverse energy, well beyond the performance of present high energy particle physics detector systems. This improved jet energy resolution is achievable with particle flow algorithms (PFA) [1, 2, 3], which make optimal use of all available information in one event by reconstructing every single particle in a jet using the best energy measurement for each particle type. For charged particles, the tracker information is used since this provides the highest precision, while neutral hadrons and photons are reconstructed in the calorimeters. This technique demands the separation of the showers of individual particles in a jet, which in turn requires extreme granularity in the calorimeters. The high granularity provides a detailed three dimensional image of the energy deposits which allows the separation of showers, photon collection efficiencies and electro-mechanical integrability. While the studies presented here were performed in the context of a highly granular hadronic calorimeter for experiments at a future linear e⁺e⁻ collider, they also apply to other calorimetric systems as well as to other detectors in high energy physics using plastic scintillator technology.

2. Test Setup

The spatial dependence of the response of scintillator tiles with directly coupled SiPMs to penetrating charged particles...
was studied with a $^{90}\text{Sr}$ source, which emits electrons with an end point energy of 2.27 MeV, yielding a sufficient fraction of particles that are capable of penetrating the scintillator tiles under study completely. The source emitted electrons through a circular collimator opening with a diameter of 1 mm. A cubic scintillator with an edge length of 5 mm was positioned in 13 mm distance underneath the tile under study as an additional trigger detector. The source and the trigger scintillator were mounted on a high precision translation stage, allowing to scan the source across the surface of the tile under study. A photograph of the experimental setup, including the support structures and the translation stage, is shown in Figure 1 while Figure 2 shows a schematic of the arrangement of the source, the tile under study and of the trigger scintillator.

Both the trigger scintillator and the different $3 \times 3 \text{ cm}^2$ tiles that were studied here were fabricated from 5 mm thick plates of Saint-Gobain BC-420 premium plastic scintillator [9]. The scintillator was enclosed with an aluminized reflective foil [10] on all sides, leaving only a small opening for the coupling of the photon sensor in the case of a simple direct coupling, and completely enclosing the tile in the case of SiPM integration as discussed below.

Light detection was performed by Hamamatsu MPPCs with an active area of 1 mm$^2$ and a pixel size of $25 \times 25 \mu\text{m}^2$, resulting in 1600 pixels per sensor. For the read out of the trigger scintillator, an MPPC in a ceramic package (type S10362-11-025C) was mounted underneath the plastic cube. The tiles under study were read out with an MPPC in a clear plastic package with a size of $3 \times 4 \text{ mm}^2$ with a thickness of 1.5 mm, a prototype of the now available SMD-mount type S10362-11-025P. In all presented measurements, the MPPC-25P was coupled directly to the center of one side face of the tile.

The MPPCs were mounted on custom designed preamplifier boards with a fixed amplification factor of 8.9. A 4-wire temperature sensor (thermistor) was placed in thermal contact with the MPPC used to read out the tile under study to monitor changes in the temperature, allowing an offline correction for the temperature dependence of the device response. The signal readout was performed with a 4 GHz, 20 GSamples/s oscilloscope with an acquisition time window of 50 ns per recorded event. The readout was triggered by requiring a coincidence of signals above the equivalent of two detected photons in the tile under study and in the trigger cube. The requirement of a coincidence in both the tile and the trigger scintillator ensured the selection of signals from electrons that fully traversed the tile under study. Due to the energy spectrum of the electrons emitted from the $^{90}\text{Sr}$ source, most of the produced electrons are absorbed fully in the tile, making this coincidence selection mandatory to obtain a good sample of penetrating particles.

The total charge of each electron signal was determined in an offline analysis procedure from the integral of the recorded wave form. The distribution of the recorded charge for 20 000 events , with the radioactive source located above the center of the tile under study, is shown in Figure 3 together with a fit of a Landau function convolved with a Gaussian. The distribution shows well-separated peaks corresponding to a certain number of fired pixels within the MPPC. A multi-gauss fit was applied to extract the peak-to-peak distance to determine the gain of the SiPM.
equivalents. The overall spectrum is a convolution of the distribution of the energy deposition in the tile by the penetrating electrons, of the photon collection statistics and of electronic noise and signal integration uncertainties. The latter two can be seen from the width of the individual photon peaks. The recorded energy spectrum does not exhibit the pronounced long tail to high energy deposits characteristic for minimum ionizing particles in thin absorbers. This is due to the low energy of the electrons used in the measurement. The mean energy loss of a minimum ionizing particle in the 5 mm thick scintillator tile is around 1 MeV, thus the requirement that the particle penetrates the tile and generates a sizeable signal in the trigger scintillator limits the amount of energy deposited in the tile under study, essentially cutting off the high energy tail of the energy loss distribution.

3. Measurement of the Uniformity of Response

The cell uniformity, which is the response of the scintillator tile with respect to the particle impact position, was determined through a lateral scan of the radioactive source across the surface of the cell under study. The source, and with it the trigger scintillator, were moved with a step size of 0.5 mm in a rectangular pattern across the tile surface, covering the full active area including the edge regions. The source was steered to 61 \times 61 positions on the tile, recording 500 electron signals and the current temperature at each point. Before every tile scan, the center of the source casing and therefore the center of the distribution of emitted electrons was aligned to the center of the tile under study. Consequently, the source was aligned to the tile edges for the outermost on-tile positions.

The position dependent mean signal height (MSH) was extracted from the signal distributions recorded at each point. Since the statistics of 500 events is not sufficient to perform a full fit of the distribution as shown in Figure 3, the mean of all recorded amplitudes is used to evaluate the response at each position.

Figure 3 shows the spatial distribution of measured MSH for a simple unmodified tile with the dimensions 3 \times 3 \times 0.5 cm³, flat polished surfaces and the MPPC-25P coupled to one flat side face of the tile. This version of the scintillator tile corresponds to the simplest possibility for a direct coupling of the photon sensor on the side of the tile, and is referred to in the following as ‘Simple Tile 5’ or ‘ST5’, where the “5” denotes the thickness of 5 mm. A pronounced non-uniformity of the response as a function of the position of the particle incidence is clearly apparent, with a significantly increased signal amplitude close to the coupling position of the photon sensor. Since the response of SiPMs shows a strong temperature dependence, the data were corrected for the ambient temperature with an offline correction procedure. The temperature of the SiPMs varied by about ±2 °C during a standard tile scan due to day-night variations in the laboratory. The dependence of the amplitude $A$, which is the most probable signal height extracted from the signal distribution of the SiPM-Tile entity, on temperature was obtained for each individual SiPM device in a separate run by recording data with the source at a representative position on the tile over an extended period with changing temperatures. In the temperature range of interest here the relative temperature dependence of the amplitude $\frac{1}{\Delta T} \cdot \frac{dA}{dT}$ is approximately constant, and was measured to be -4.4%K for the MPPC-25P. The MSH then was corrected by a scale factor $S$ calculated for each position:

$$MSH_{Corr}(x, y) = MSH_{Uncorr}(x, y) \cdot S,$$

where

$$S = \left(1 + \frac{1}{\Delta T} \cdot \frac{dA}{dT} \right)^{-1}$$

with $\Delta T$ giving the difference of the temperature at the point of measurement to the mean temperature over the full measurement period.

4. Data Analysis

A method was developed to quantify the response and uniformity of a tile and enable a comparison of the performance of different tile geometries. The response of the tile ST5, with a directly coupled photon sensor without any modifications to the scintillator is shown in Figure 3. It is characterized by a steep overshoot at the SiPM coupling position, a sharp drop at the tile edges and a quasi-constant response over most of the remaining active area. To characterize the mean response of a tile to penetrating minimum ionizing particles without strong influence from the non-uniformities due to the photon sensor coupling, the overall mean signal height (OMSH) for a given tile is defined as the mean value of all measurement points outside the extreme regions of the distribution, taken over the inner rectangle shown in Figure 3. The exact location of the tile within the scanned area can also be clearly identified by the signal drop at the tile edges and is illustrated by a black square with an edge length of 3 cm.

The mean signal amplitude for a penetrating minimum ionizing particle is a crucial performance parameter of the SiPM-scintillator tile entity. It is a compromise between a high signal-to-noise ratio for single particles and a large dynamic range, limited by the finite number of pixels on the photon sensor. The latter requirement makes large signal yields unattractive. Hence, a most probable signal height of about 15 photon equivalents (p.e.) is considered optimal. By an appropriate choice of the bias voltage of the photon sensor a signal yield in this region was achieved in the CALICE AHCAL prototype using tiles with embedded wavelength shifting fiber.

To quantify the non-uniformity, we defined a range of ±5%, ±10% and ±20% around the OMSH and determined the fraction of the tile area with $MSH$ values within the respective ranges. The quality of the tile uniformity is judged by these area fractions, with the goal to achieve a large area of the tile within the ±5% band. Note, however, that the values for all ranges will always be below 100% when taking the full tile area into account because of the finite size of the collimator opening of the radioactive source and the geometrical acceptance of the trigger scintillator, which leads to the inclusion of electrons which only penetrate part of the tile in the edge regions in the signal sample.
This results in smeared measurement at the tile edges. To eliminate those setup specific edge effects, we provide a second set of area fractions in which measurements at the tile edges were cut, and a region of 1.25 mm around the tile edges was ignored. In this case, the effectively investigated tile area is reduced to $27.5 \times 27.5$ mm$^2$.

5. Optimization of the Tile Geometry

Scintillator cells with direct fiberless SiPM coupling are only applicable in highly granular calorimeters if their architecture allows dense packing of the cells to eliminate inactive zones, if they deliver a single particle signal amplitude in the desired range providing a good signal-to-noise ratio and a high dynamic range, and if they achieve a high uniformity of the signal response with respect to the position at which a particle traverses the tile. These requirements can be fulfilled by modifications of the tile geometry. The machining procedure has to be kept simple to allow for mass production of the tiles.

A gradual reduction of the scintillating material close to the photon sensor should reduce the overshoot of the response observed for unmodified tiles of the type ST5. Such a concept was already successfully applied in tile optimization studies with bottom face coupling [8]. To provide full compatibility with the layer-integrated electronics board for the next generation HCAL prototype currently under development at DESY [11] within the CALICE collaboration, we adapted this approach to the coupling of the photon sensor to the center of one side face. To allow seamless packing of the scintillator cells, the SiPM was embedded into the plastic material.

In several iterations with varying geometries, an optimized tile design was developed. Figure 6 illustrates the overall concept of the tile design that was further investigated here. A slit with the dimensions of 2 mm, 4 mm and 5.5 mm in height, width and depth was drilled into the tile. Figure 6 shows the
modified tile, including the integration opening for the photon sensor and the machined slit. The slit has to reach significantly into the tile to deflect an increased fraction of propagating photons into the direction of the SiPM. Additionally, the drilling procedure leaves a fine surface structure on the dimple which refracts incident light diffusely and disperses it likewise for near and distant particle penetration positions. This slightly increases the collected light signal per particle while reducing non-uniformities.

To allow close packing of the tiles, as required for the active layers in a calorimeter, the photon sensor has to be integrated into the scintillator cell to provide a flat tile face. This is achieved by machining a rectangular hole that matches the dimensions of the SiPM casing into the tile side face at the position of the slit, as shown in Figure 7. This hole also provides the alignment of the sensitive surface of the SiPM to the center of the machined slit. After the insertion of the SiPM, the side face of the tile was completely covered with reflective foil. This integration of the photon sensor increased the light collection efficiency significantly compared to the external coupling used for the ST5 tile. In contrast to a tile with embedded WLS fiber, as used in the present CALICE physics prototype [2] (see Figure 5), where the SiPM has to be aligned precisely with the fiber to ensure a full coverage of the fiber cross section, the tolerances on the SiPM positioning are very generous in case of our presented tile design. The performance of the SiPM-tile entity remains stable, provided the SiPM ‘looks’ through the drilled slit into the tile. Tiles with the modifications discussed here will be referred to in the following as ‘tile with slit and SiPM integration’ or, in short, ‘SI’. Both 5 mm thick tiles (SI5) and 3 mm thick tiles (SI3) have been studied extensively.

Figure 7: Dimensions (in mm) of the 5 mm thick scintillator tile with a geometry optimized for response uniformity and signal amplitude, as discussed in the text. A 5.5 mm deep, 4 mm wide and 2 mm high slit to improve the uniformity and a 1.5 mm deep hole with a cross section of 4.5 × 4 mm² to allow the full integration of the photon sensor were drilled into the scintillator material.

| Tile     | OMSH       | ±5%   | ±10%  | ±20%  |
|----------|------------|-------|-------|-------|
| ST5      | 13.0 p.e.  | 57.4% | 80.8% | 90.7% |
| ST5 (cut)| 69.1%      | 93.8% | 98.3% |
| SI5      | 18.4 p.e.  | 72.7% | 84.2% | 90.1% |
| SI5 (cut)| 87.9%      | 97.1% | 98.9% |
| SI3      | 13.0 p.e.  | 70.3% | 84.3% | 94.0% |
| SI3 (cut)| 82.5%      | 94.0% | 98.0% |

Table 1: The uniformity of three different tiles: Unmodified tile with direct SiPM coupling (ST5) and tiles with applied slit and integrated SiPM coupling in an 5 mm (SI5) and 3 mm (SI3) option. Shown is the overall mean of the signal height (OMSH) and the tile area within a deviation from this value in three different ranges. The values labelled “cut” are determined over a reduced area of the tile, excluding the edge regions which suffer from inaccuracies due to the acceptance of the setup, as discussed in the text.

6. Results

The performance of scintillator tiles with the modifications discussed above and with a thickness of 5 mm (SI5) and 3 mm (SI3) has been quantified and compared to the performance of unmodified tiles of the type ST5 with respect to the OMSH and the uniformity. Table 1 summarizes the measurements of the overall mean signal amplitude and of the uniformity of the response over the tile surface.

The value of the OMSH of the modified SI5 tile increased by 42% compared to the ST5 tile from 13.0 p.e. to 18.4 p.e., reaching the optimal range for excellent signal and noise separation. Also the uniformity of the tile response was significantly improved by the modifications, as shown in Figure 8. The response to penetrating particles was constant to a good approximation over most of the tile area, apart from a minimal signal overshoot at positions in direct proximity of the slit machined into the scintillator and a decrease in the area of the slit itself which amounts to 25% of the OMSH. As expected, the response is decreased at the position where the SiPM was integrated into the tile, but note that it drops nowhere below a value of 12.5 p.e., demonstrating that the whole tile area was highly sensitive to traversing particles. Comparing the values for the area fractions listed in Table 1 we find that the uniformity of a SI5 tile improves by 27% and 4% in the ±5% and ±10% region, respectively.

The same modifications were also investigated for tiles of 3 mm thickness (SI3), and show a comparable performance in terms of response uniformity, as summarized in Table 1. Due to the reduced thickness, the overall signal amplitude was reduced compared to SI5, and was in the same range as for the unmodified directly coupled 5 mm thick tile ST5. Thinner tiles are of considerable interest for calorimeters at future collider detectors, since they allow a higher average density of the detector for a given sampling frequency. This makes more compact calorimeters possible, reducing the required radius of the experiment’s solenoidal magnet for a given maximum energy leakage, resulting in significant cost savings.
7. Conclusion

Direct fiberless coupling of silicon photomultipliers to plastic scintillator tiles, made possible by blue sensitive SiPMs, allows significant simplifications of the scintillator tile construction, and consequently potential cost and time savings in the construction of highly granular analog calorimeters. However, specific modifications of the tile geometry are necessary to provide a large signal for fully penetrating minimum-ionizing particles and a high degree of uniformity of the response over the full active area.

We have developed specific modifications for tiles with SiPMs coupled to the center of a side face of the cell. These consist of a drilled slit in the scintillator and a hole to allow the full integration of the photon sensor, to achieve a high degree of uniformity and a satisfactory signal amplitude for both 5 mm thick and 3 mm thick scintillator tiles with lateral dimensions of $3 \times 3$ cm$^2$. The direct coupling also significantly relaxes the required alignment precision of the photon sensor, simplifying the assembly and the mass production of scintillator tile - SiPM units. The studies were performed in the context of highly granular hadron calorimetry, but the developed scintillator cell design is also suitable for other applications in which a high level of integrability, cell uniformity or efficiency is needed for particle detection.

References

[1] J. C. Briant and H. Videau, “The calorimetry at the future e+ e- linear collider,” in Proc. of the APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001) ed. N. Graf, Snowmass, Colorado, 30 Jun - 21 Jul 2001, pp E3047 [arXiv:hep-ex/0202004].

[2] V. L. Morgunov, “Calorimetry design with energy-flow concept (imaging detector for high-energy physics),” Prepared for 10th International Conference on Calorimetry in High Energy Physics (CALOR 2002), Pasadena, California, 25-30 Mar 2002.

[3] M. A. Thomson, Particle Flow Calorimetry and the PandoraPFA Algorithm, Nucl. Instrum. Meth. A611 (2009) 25–40.

[4] C. Adloff, et al., Construction and commissioning of the CALICE analog hadron calorimeter prototype, [arXiv:1003.2662] [physics.ins-det], submitted to JINST.

[5] V. Golovin, V. Savelev, Novel type of avalanche photodetector with Geiger mode operation, Nucl. Instrum. Meth. A518 (2004) 560–564.

[6] The ILD Concept Group, The International Large Detector - Letter of Intent, March 2009, [http://www.ilcild.org/documents/ild-letter-of-intent/LOI.pdf]

[7] Hamamatsu Photonics K.K., [http://www.hamamatsu.com]

[8] G. Blazey, et al., Directly coupled tiles as elements of a scintillator calorimeter with MPPC readout, Nucl. Instrum. Meth. A605 (2009) 277–281.

[9] Saint-Gobain BC-418, BC-420, BC-422 Premium Plastic Scintillators - Data Sheet, [http://www.detectors.saint-gobain.com/Plastic-Scintillator.aspx]

[10] 3M, St. Paul, MN, USA, [http://www.3m.com]

[11] P. Göttlicher, First results of the engineering prototype of the CALICE tile hadron calorimeter, IEEE NSS/MIC Conference Record, Orlando, FL, USA, October 2009.