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2017 J. Phys.: Conf. Ser. 798 012218

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# Geant4 simulation of optical photon transport in scintillator tile with direct readout by silicon photomultiplier

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**Abstract.** The direct coupling of silicon photomultiplier to the scintillator tile is considered to be the main option for active elements of the highly granular hadron calorimeter developed for future linear collider experiments. In this study, the response of the scintillator–SiPM system to minimum ionising particles was simulated using the optical photon transport functionality available in the GEANT4 package. The uniformity of response for both flat tile and tile with dimple was estimated from the simulations and compared to the experimental results obtained in the previous studies.

## 1. Introduction

The highly granular calorimeters represent a new concept in the detector design for both high energy physics and other applications. This concept was developed for the detector system of the future linear collider experiments with the aim to apply the particle flow approach [1] and achieve an unprecedented jet energy resolution [2]. The highly granular calorimeter prototypes developed by the CALICE collaboration were intensively tested during several test beam campaigns and the proof-of-principle for such systems has been successfully demonstrated [3]. Though the highly granular design of the calorimeter system provides an opportunity to perform a sophisticated analysis and improve resolution, it also poses new challenges as for the construction and calibration of the detector system is concerned. The baseline design of the ILD detector for the ILC project considers the scintillator tiles readout by silicon photomultipliers (SiPM) as the main option for the hadron calorimeter [4]. Very high longitudinal and transverse segmentation of the highly granular hadron calorimeter means that the number of channels, i.e. scintillator tiles with individual readout, will be  $\sim 10$  millions. For this reason, the design of the tile is preferred, which simplifies the mass production and assembly processes.

In the first prototype of the CALICE analogue hadron calorimeter assembled from the scintillator tiles with SiPM readout [5], the wavelength shifting (WLS) fiber was used to collect the scintillation light and deliver it to the SiPM in each tile. The coupling of the SiPM to the fiber provides an appropriate uniformity of response though the transverse size of the tile ( $3 \times 3 \text{ cm}^2$  in the central part of the calorimeter) is much larger than the SiPM window ( $\sim 1 \times 1 \text{ mm}^2$ ). The direct readout concept without WLS fiber was investigated and tested in refs. [6, 7, 8, 9].



Such an approach requires a more complicated shape of the tile surface to achieve uniformity comparable to that of the tile with WLS fiber.

In this study, the simulation of response to a minimum ionising particle (MIP) of the scintillator tile directly readout by SiPM was performed using the GEANT4 package [10]. The experimental setup and conditions used in the experimental study from ref. [9] were reproduced and the results of simulations were confronted with the experimental data to adjust the model parameters.

## 2. Simulation of the experimental setup

The optical photon transport functionality of the GEANT4 package was used to simulate the propagation of light generated by MIP in the scintillator tile and the collection of photons by SiPM. The geometrical parameters of the simulated tile—SiPM system follow the design described in detail in the experimental study from ref. [9].

### 2.1. Geometrical parameters

The tile is made from the polystyrene-based scintillator (PS) with the sizes  $30 \times 30$  mm<sup>2</sup> along  $x$  and  $z$  coordinates and 3 mm along  $y$  coordinate. The perimeter faces of the tile are painted by the coating from the foamed polystyrene, while both top and bottom big faces are covered by the mylar mirrors. The top mirror has a hole, which holds the SiPM inside the box made from epoxy resin. In simulations, the SiPM material is Si and the SiPM window, where photons are absorbed and detected, has a size of  $2.2 \times 2.2$  mm<sup>2</sup>, which corresponds to the size of the SiPM window used in the experiment.

Two geometrical configurations were simulated: the tile with the flat top surface and the tile with the dimple milled in the center of the top surface. In both cases the SiPM is centered in the  $(x, z)$  plane. For the flat design, the SiPM is placed directly on the tile top surface. For the dimple configuration, the following optimal design from ref. [9] was simulated: the dimple depth in the centre is 1.8 mm, the dimple radius is 8 mm and the bottom of the SiPM box is by 0.95 mm below the top surface level of the tile. The additional trigger tile placed below the main tile was simulated to reproduce the trigger conditions in the experimental setup.

### 2.2. Particle source

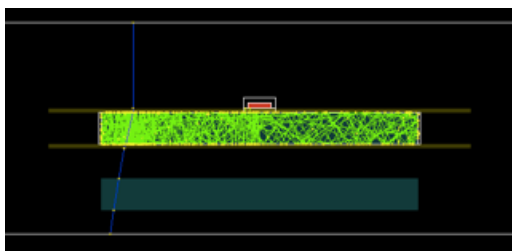
The simulated source of  $\beta$ -particles has a circle shape with a width of 1.5 mm and is placed above the tile. The energy distribution of the emitted particles covers the range 1.5–2.28 MeV and corresponds to the tail of the energy distribution of electrons from the <sup>90</sup>Sr source, which was used in ref. [9]. As follows from the simulations, the probability to reach the trigger tile drops down rapidly for electrons with the energies below 1.5 MeV. An example of the event display is shown in figure 1.

### 2.3. Optical properties

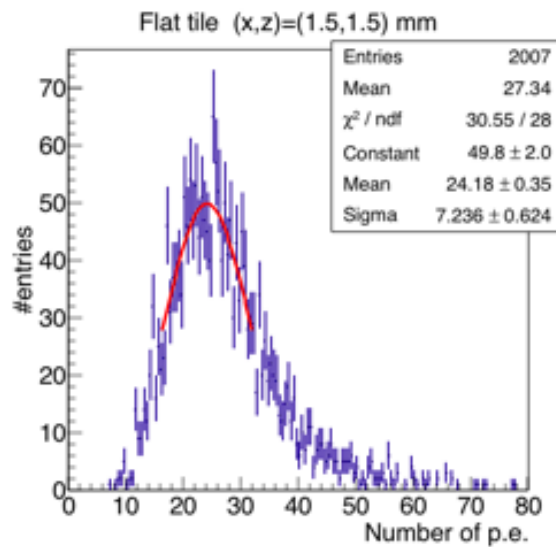
The optical photon transport functionality of the GEANT4 package provides a possibility to set the optical properties for both bulk materials and surfaces. The main parameters used in the simulations are listed in table 1. As the exact optical characteristics are unknown, the variation of some parameters were performed to find the best agreement with the experimental results. The light emission spectrum for polystyrene is provided by GEANT4 and has its maximum at  $\sim 400$  nm. The wavelength dependence of the absorption length follows the absorption spectrum of polystyrene with the maximum value shown in table 1. The specular reflection for mirror and the diffuse reflection for coating were applied in simulations.

**Table 1.** Material and surface properties in simulations.

Fixed parameters		Varied parameters	
Light yield of PS	5.0/keV	Max. absorption length in PS	20–200 cm
Refractive index of PS	1.58	Reflectance of mylar	0.85–0.98
Refractive index of epoxy resin	1.50	Reflectance of coating	0.65–0.95
Reflectance of SiPM window	0.05	Absorption length in coating	20–50 $\mu\text{m}$



**Figure 1.** Visualization of the event simulated for the flat tile configuration in GEANT4. The blue line shows the track of  $\beta$ -particle, the light green lines are the tracks of optical photons, the red box is a schematic view of the SiPM. The bottom dark green box is the trigger tile. The mylar mirrors are shown with the thick brown lines.

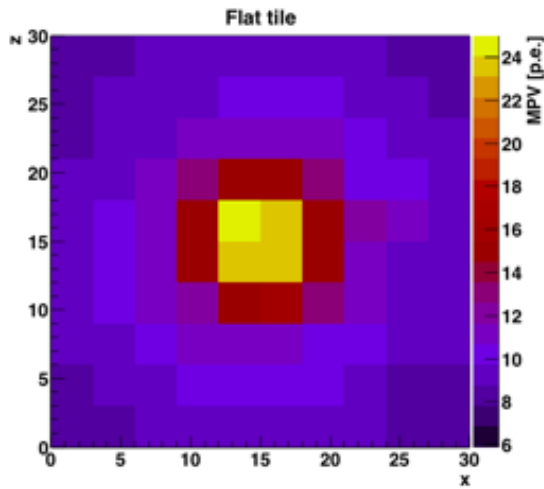


**Figure 2.** Distribution of the simulated response to MIP for the flat tile when the source is positioned at the distance  $(x,z)=(1.5,1.5)$  mm from the centre of the tile. The red curve shows the Gaussian fit.

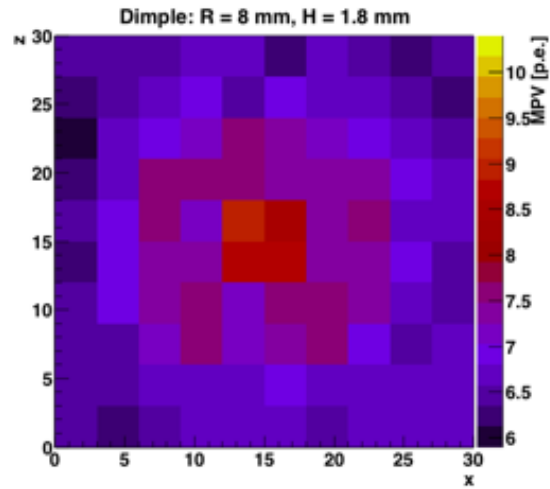
#### 2.4. Digitisation

The number of generated photons, which cross the boundary between the epoxy resin and SiPM surface and fall into the SiPM window, were counted. In addition, the trigger variable is set to 1 if the primary particle reaches the trigger tile. Then the digitisation procedure is needed to convert the number of photons into the number of photoelectrons (p.e.) generated in SiPM. As the SiPM structure was not simulated, the number of photoelectrons is obtained from the Poisson distribution with the mean equal to the number of counted photons in the given event and multiplied by factor 0.15, which takes into account the quantum efficiency and geometry factor of the SiPM cell area. Then the Gaussian noise is added to the signal with the mean and sigma equal to 3 and 2 photoelectrons, respectively.

The distribution of the response to MIP ( $\beta$ -particle) after digitization is shown in figure 2 for the flat tile configuration and the position of the particle source near the centre of the tile. The distribution from figure 2 contains events, which pass the trigger requirement. The most probable value (MPV) of the response distribution after digitisation is found from the two-step Gaussian fit in the range  $\pm 1.5$  RMS (root mean square deviation). The same fit procedure was used in ref. [9].



**Figure 3.** Simulated response to MIP vs. source position in the  $(x,z)$  plane for the flat tile design. Scan step is 3 mm.



**Figure 4.** Simulated response to MIP vs. source position in the  $(x,z)$  plane for the tile with dimple. Scan step is 3 mm.

### 3. Results

The simulation of the response to MIP was performed for the different distances of the particle source from the tile centre in the transverse direction. As the big face of the tile is square, the simulation was done for one octant only, which was scanned with the step 3 mm by moving the position of the source in the  $(x,z)$  plane. To fill the full plane, the digitisation procedure described above was repeated 4 times for each diagonal position ( $x = z$ ) and 8 times for other source positions exploiting the symmetry of the design. An example of dependences of the extracted MPV on the source position in the  $(x,z)$  plane is shown in figure 3 and 4 for the flat and dimple tile designs, respectively. The following values of varied parameters from table 1 are used for these plots: the absorption length of PS is 1 m, the absorption length of coating is  $50 \mu\text{m}$ , the reflectance of mylar mirror is 0.98 and the diffuse reflectance of coating is 0.95. The uniformity was defined in ref. [9] as a ratio of the RMS of the MPV to the mean MPV calculated for all positions over the tile. Following this approach one can estimate the uniformity to be 30.2% (mean MPV = 10.7 p.e.) for the flat design in figure 3 and 7.9% (mean MPV = 6.9 p.e.) for the dimple design in figure 4.

The dependence of the simulated response on several parameters was also investigated. The dependence on the polystyrene absorption length was found to be rather weak in the range studied and similar degradation of response with absorption length is observed for both flat and dimple configurations. The maximum of the PS absorption lengths was set to 1 m for the further uniformity studies. The absorption length of the coating does not affect the number of photons which reach SiPM, it might affect the amount of the light cross talk between neighbour tiles, which is out of the scope of this study. The reflectance of the mirrors,  $R_M$ , and the coating,  $R_C$ , are parameters, which influence on the number of collected photons and the resulting uniformity is the most significant, as expected. It was found that the best agreement with the experimental data can be achieved for  $R_C = 0.8$  and  $R_M = 0.95$ . For these values of reflectance, a comparison of the simulations with experimental results from ref. [9] is shown in table 2. The estimated uniformities from data and simulations are in good agreement for both configurations. At the same time, the trend for the mean number of photoelectrons is not reproduced in simulations. For the flat tile design, the mean MPV is 1.5 times larger in simulations than in data, while for the dimple design it is 1.5 times larger in the experimental data.

**Table 2.** Comparison of the uniformity and mean response from the simulations with the experimental results from ref. [9].

	<b>Flat design</b>		<b>Dimple design</b>	
	Simulations	Experiment[9]	Simulations	Experiment[9]
Mean MPV (p.e.)	11.3	7.6	8.0	12.5
Uniformity (%)	24.5	21.0	6.5	8.8

#### 4. Conclusion

The validation of simulations is very important for optimisation of detector elements developed for future detector upgrades and new applications. A response to minimum ionising particles of the scintillator tile with direct readout by SiPM was simulated using the optical photon transport functionality of the GEANT4 package. The response dependence on the source position with respect to the tile centre, where SiPM is placed, is well reproduced in simulations. Though the uniformity differences between the flat and dimple designs are in good agreement between data and simulations, the changes in mean number of photoelectrons show the opposite trend. To explain this discrepancy, other geometrical and optical characteristics, such as a shape of the dimple and milled surface optical properties, need to be investigated in more detail.

#### Acknowledgments

The work has been partially sponsored by the Russian Ministry of Education and Science contracts 4465.2014.2 and 14.A12.31.0006 and by the RFBR grant 14-02-00873A. The authors would also like to thank for the support from National Research Nuclear University MEPhI in the framework of the Russian Academic Excellence Project (contract No. 02.a03.21.0005, 27.08.2013).

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