Fine shashlik simulation from tests results

M. Prokudin, I. Korolko

SSC RF ITEP, Bolshaya Cheremushkinskaya 25, 117218 Moscow, Russia
E-mail: Mikhail.Prokudin@cern.ch

Abstract. We have studied the response uniformity of the LHCb electromagnetic calorimeter modules in a beam of high energy muons. Tests of prototype module built with thin (0.5 mm) absorber and scintillator plates were performed as well as transverse scans of an ECAL module with 50 GeV electrons. To understand the light collection uniformity a dedicated Monte Carlo program for the the light propagation in different scintillator tiles was developed. Parameters of this program are tuned and checked using experimental data.

1. Introduction

During last 25 years sampling calorimeters of ”shashlik” type have proven their applicability for a wide range of high energy physics experiments. This type of calorimeter was successfully operated at PHENIX [1] at BNL, DELPHI [2] at CERN and HERA-B [3] at DESY. Wave length shifting (WLS) fibers used for the scintillator light readout allow us to build hermetic calorimeters with minimal amount of dead material. Fast response, adequate energy resolution, radiation resistance, flexible transverse and longitudinal granularity of these detectors and relatively moderate cost make them very attractive to use in large modern experiments. Last years we are developing the ”shashlik” technology trying to improve the calorimeter energy resolution and to decrease the Moliere radius.

The energy resolution of ”shashlik” calorimeter is described with a following formula:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b,$$

where \(a\) and \(b\) stand for the sampling and constant terms respectively. The sampling term depends on a thickness of absorber plates and photostatistics. An obvious wish to minimize the sampling term dictates the choice of thin (down to 0.3 — 0.5 mm) absorber plates. At the same time the very high multiplicities of modern high energy physics and nuclear physics experiments have to be taken into account. Overlapping showers from neighbour tracks considerably dilute the intrinsic energy resolution and identification power of a calorimeter with poor segmentation (large Moliere radius). To minimize Moliere radius one should also use thin scintillator tiles. On the other hand, the constant term of energy resolution is determined by transverse nonuniformity of light collection efficiency in scintillator tiles. This nonuniformity rises with decreasing the scintillator thickness worsening the constant term significantly. We have performed detailed studies of light collection efficiency in ”shashlik” calorimeter modules built with thick (4mm) and thin (0.5mm) scintillator tiles. Test beam measurements of outer, middle and inner modules of the LHCb electromagnetic calorimeter [4] were complemented with investigation.
of new "shashlik" module, which consists of 280 alternating layers of 0.5mm thick absorber and scintillator.

To understand the light collection quantitatively a dedicated ray-tracing program and corresponding optical model of scintillator tile readout with WLS fibers were developed. The parameters of the optical model were extracted from the experimental data collected during muon scan of the LHCb calorimeter inner and outer modules. Independent measurements performed with new module were used to study the dependence of light collection uniformity on scintillator tile thickness. Finally all Monte Carlo parameters were crosschecked by comparison of simulation predictions with electron scan data obtained for the LHCb inner module.

2. Experimental measurements

Experimental studies of the calorimeter modules were performed at the X7 beam which is a part of the West Area test beam complex at CERN. The beam momentum settings were used in the range between 5 and 100 GeV/c. Beam polarity was negative, and particles available were $\pi^-$, $e^-$ and $\mu^-$. The electron beam was produced using a lead sheet to convert photons from neutral pion decays, while the muon beam used a beam dump to absorb all secondary particles except muons.

The beam line was instrumented with scintillator counters to form the beam trigger. Three sets of delay wire chambers [5] with a typical spatial resolution of 0.2 mm were used to reconstruct the beam particle trajectory and to determine the particle entry point at the calorimeter module surface. The arrangement of tested calorimeter modules and delay wire chambers at the beam line is shown in Figure 1.

The calorimeter modules were assembled in a $3 \times 3$ array: the tested module was put in a center of assembly, while other 8 modules were used to control the leakage of electromagnetic shower. Uniformity of the calorimeter response for muons was measured with central module only because the net energy leakage to all neighbor cells was less than electronics noise in these channels. High statistical samples of 100 GeV/c muons were used to scan the surface of the calorimeter cells with $1 \times 1$ mm$^2$ step. The obtained at every step signal distribution was then fitted with Landau function. Determined most probable values were stored in a 2D histogram representing the response uniformity of a given calorimeter cell to muons. For the outer LHCb module $1 \times 2$ mm$^2$ steps were used because of a limited statistics.

For electrons the energy was collected in a central module and 4 modules on top, bottom, right and left from the center. The net signal in four corner modules was comparable with the noise of electronics. The front face of the calorimeter cell was scanned with $1 \times 1$ mm$^2$ step. Individual signal distributions were then fitted with Gaussian. The positions of distribution maximum were stored in a 2D histogram representing the response uniformity of a given calorimeter cell to electrons.
3. Light collection modelling

A dedicated ray-tracing program was developed for modelling light collection inside the scintillator cell. Optical processes handled by the ray-tracer involve refraction, mirror and diffuse reflection, attenuation in medium and absorption on plastic surface and in tyvek which is used to interlay plastic and absorber tiles. Optical properties of all surfaces and media depend on photon wavelength to model the dispersion. Additional dependence on local tile coordinate was added for modelling light masks. The geometry of plastic tiles is defined by a set of primitives (cuboids, cone and cylinder) and Boolean operations with them. A dedicated voxelization [6] procedure is used to speed up calculations. The photon is assumed to propagate along the straight line between two interactions neglecting diffuse scattering in the scintillator medium.

Tiles have cuboid shape with cylindrical holes for WLS fibers and one clear fiber in the centre of every cell. The edges of the tile are assumed to be coated with special white paint simulating the diffuse reflection due to the special chemical treatment used during mass production. The same white paint also covers thin (1.0 — 1.5 mm) bands at the very edge of top and bottom surfaces of the tile. A scintillator tile with all fibers is covered with tyvek sheets from both sides. Photons are generated uniformly inside tile volume with isotropic momentum distribution. Photon wave length is generated according to the POPOP emission spectra. Each photon is propagating inside described setup until its stop in scintillator or absorption on the tile surface, in the tyvek or in the fiber core. Photon stopped in the fiber core is reemitted isotropically with shifted wavelength corresponding to the WLS fiber reemission spectrum. The direction of reemitted photon is then checked to ensure that it is not able to leave the fiber and will reach the photomultiplier sensitive window. Small attenuation in the light mixers located between fibers bundle and PMT is neglected. Computed 2D map of light collection efficiency is finally convoluted with the measured map of the tile thicknesses which determines the energy deposition for minimum ionizing particle crossing the tile in a given point perpendicular to its surface. The last step is important because plastic tile thickness is not constant with a current mass production technology. The result of such convolution is referred later as an effective 2D map of light collection efficiency.

The results of ray-tracing program depend on certain number of parameters such as: photon attenuation length in scintillator, whiteness of tyvek and quality of white paint covering tile edges, probability of photon absorption on the surface of plastic tile (so called surface quality) and some others. All these parameters could be extracted from the comparison of simulation results with the experimental measurements of light collection uniformity. Such comparison should take into account the transverse shape of incoming particle energy deposition in the calorimeter module which dilute the intrinsic variation of light collection. Muon data is therefore most suitable for our purposes. Effective 2D maps of light collections were used in GEANT3.21 [7] program for weighting of each elementary energy deposition depending on the local coordinate in calorimeter cell. The similar simulation chain was then repeated for electrons with selected set of effective 2D maps as a cross-check. The inner module of the LHCb calorimeter was also modeled with Geant4 [8] transport code. The results of two GEANT versions are identical. Algorithms of incoming particle energy reconstruction after GEANT simulation correspond exactly to those used in the analysis of test beam data. Tuned set of ray-tracing program parameters allow us to reproduce the experimental data almost perfectly.

4. Comparison of simulation with experimental data

Experimental results obtained for the inner calorimeter cell are presented in Figure 2 for two 1 mm wide bands — passing over the fiber positions (lower plot) and located between two fiber rows (upper plot). Hatched histogram shows the GEANT predictions convoluted with effective 2D light collection efficiency maps from our dedicated simulations. Global nonuniformity is negligible. Special chemical treatment of tile edges increased the light collection efficiency,
compensating effects of dead material between modules. Results for the middle calorimeter module are very similar. In the outer modules the inter-fiber distance is significantly higher (15 mm instead of 10 mm in other modules). Corresponding experimental results for the outer calorimeter module are presented in Figure 3 together with GEANT simulation predictions. Visible variation of the MIP particle response is diluted with worse spatial resolution of the tracking system used at that time period. Increased inter-fiber distance smoothed the behavior of light collection efficiency between the fibers. The quality of diffuse light reflection and the width of painted bands were found to be the most important parameters of optical model. The last important parameter was the quality of scintillator tile surface. The dependence of light collection efficiency variations on several other factors (like refraction index of the scintillator, attenuation length of the scintillator) was found to be almost negligible.

Electromagnetic showers are much wider in comparison with almost point-like energy depositions of minimum ionizing particles. Therefore the variations of reconstructed energy for electrons and photons are considerably reduced. The results of a lateral scan of the LHCb inner module with 50 GeV/c^2 electrons are shown in Figure 4. In the cell of the inner module we observed 0.5% variation of response. This cell is located in the centre of the module and therefore the effects of dead material are diminutive. The variation of the ECAL response to electrons and photons from the LHCb events would be significantly decreased due to the nonzero impact angles.

The response uniformity of the prototype module is shown in Figure 5. In comparison with the LHCb inner module the prototype has significantly thinner scintillator tiles, where the light collection uniformity is much worse. This effect is explained by a finite probability for photon to be captured on the scintillator tile boundary. In thin tiles a number of reflections photon undergoes to travel till absorption if WLS fiber is much higher than in thick tiles. So the probability of absorption is also higher.

The optical model with extracted parameters was used to calculate the overall light yield

![Figure 2](image.png)

**Figure 2.** The response uniformity of the inner LHCb module measured with muons (error bars) and simulated (hatched histogram). The scan was made in 1mm wide bands between two fiber rows (upper) and through the fiber positions (bottom).
Figure 3. The response uniformity of the outer LHCb module measured with muons (error bars) and simulated (hatched histogram). The scan was made in 2mm wide bands between two fiber rows (upper) and through the fiber positions (bottom).

for all tested modules. Ray-tracing program was not tuned to reproduce the absolute value of light yield; therefore we have used the inner module simulation results for normalization.

Figure 4. Uniformity of response to 50 GeV/c² electrons of the inner module (error bars) compared with simulation results (hatched histogram). The scan was made in 1mm wide bands between two fiber rows (upper) and near bottom fiber row (bottom). The average response of the module for experimental data and MC simulation was normalized to unity.
Figure 5. The response uniformity of the prototype module measured with muons (error bars) and simulated (hatched histogram). The scan was made in 1mm wide bands between two fiber rows (upper) and through the fiber positions (bottom).

on experimental data. The comparison of Monte Carlo predictions with data is presented in Table 1. The data for cosmic stand are taken from [9].

Table 1. Light yield for different modules.

|            | LHCb inner | LHCb middle | LHCb outer | prototype |
|------------|------------|-------------|------------|-----------|
| Test beam  | 3000 ± 150 | 3600 ± 180  | 2500 ± 130 | 700 ± 60  |
| Cosmic stand | 3100 ± 130 | 3500 ± 170  | 2600 ± 120 | no data   |
| Modeling   | 3000       | 3600        | 2570       | 600       |

5. Conclusion
Using the tuned ray-tracing program we have calculated the 2D maps of the light collection efficiency for three different technologies of “shashlik” scintillator tiles production:

- tiles with transparent edges;
- tiles with mirrored edges (ideal mirror);
- tiles with matted edges and bounds near edges (LHCb like).

The results are presented in Figure 6, averaging over narrow (1 mm wide) bands precisely in between the fiber rows. Tiles with transparent edges have the lowest and most non-uniform light collection efficiency. Mirroring of the tile edges allows to increase the light yield by a factor of 3 and improves the uniformity, but does not compensate dead material effects. Chemical treatment of tile edges and bounds near edges resulting in a diffuse reflection of the scintillating
light allows a factor of 2 increase of overall light yield and compensates the decrease in detector response on the outer borders of the calorimeter modules due to dead material.

![Figure 6. Light collection efficiency simulated for transparent (squares), mirrored (stars) and matted (solid dots) tiles](image)

The uniformity of the LHCb calorimeter response was measured at the test beam and modeled. The model is able to describe the response uniformity with unique set of parameters. It also describes the overall light yield data with the same set of parameters. This model will be used in simulation of LHCb calorimeter response and for the development of new "shashlik" calorimeters with better energy resolution and small Moliere radius.

References
[1] Adcox K et al. (PHENIX) 2003 Nucl. Instrum. Meth. A499 469–479
[2] Benvenuti A C et al. Given at 4th International Conference on Calorimetry in High-energy Physics, La Biodola, Italy, 19-25 Sep 1993
[3] Hartouni, E and others DESY-PRC-95-01
[4] Amato S et al. 2000 LHCb calorimeters Technical Design Report Technical Design Report LHCb (Geneva: CERN)
[5] Spanggaard J 1998 Delay Wire Chambers — A User Guide (Preprint CERN-SL-98-023-B1)
[6] Arie Kaufman and Daniel Cohen and Roni Yagel 1993 Computer 26 51–64 ISSN 0018-9162
[7] 1993 Geant3. CERN Program Library Long Writeup (Preprint W5013)
[8] Agostinelli et al 2003 NIM A 506
[9] Aref’ev A et al. 2008 Design, construction, quality control and performance study with cosmic rays of modules for the LHCb electromagnetic calorimeter Tech. Rep. LHCb-2007-148. CERN-LHCb-2007-148 CERN Geneva