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Fiber density and uniformity of response of LHCb electromagnetic calorimeter

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Abstract

Discussed is the transverse uniformity of response and the choice of fiber density for the electromagnetic calorimeter of the LHCb experiment at CERN. Response uniformity is optimized by choosing proper tile edge coverage and the density of fibers. Using of side masks is also discussed.

"Shashlik" electromagnetic calorimeter is an important part of LHCb calorimeter system, its design, performance requirements and physics tasks are described in detail elsewhere [1]. Present paper addresses the optimization of calorimeter performance in view of light yield and response uniformity.

Three types of modules are planned to use in LHCb electromagnetic calorimeter for the inner, middle and outer zones. The modules of all three sections have similar design and identical transversal size of $12.12 \times 12.12\ cm^2$. The number of calorimeter cells per module and the fiber density are however different. We foresee 9, 4 and 1 cell per calorimeter module and 16, 36 and 64 fibers [1] per cell, to be used for the inner, middle and outer regions respectively.

[1] Choice of fiber density for outer region modules is discussed below.

For a given cell size and sampling fraction the energy, and in a lesser extent, spatial resolution of the "shashlik" module is determined by response uniformity.

Energy resolution of "shashlik" modules, structured similar to the final LHCb design, was measured with the electron beam at DESY [2] to be [2]

$$\frac{\sigma_E}{E} = \frac{9.5\%}{\sqrt{E}} \oplus 1\% \quad (E\ in\ GeV) ,$$

which is in excellent agreement with Monte Carlo simulation studies.

Since those measurements, we studied possible modification of the module design in order to improve response uniformity and optimize the cost.

Transverse non-uniformity in WLS fiber light collection comes predominantly from two sources: non-perfect light reflection from tile edges (the so-called global non-uniformity effect), and shower position with respect to the fibers (local or inter-fiber non-uniformity).

Global non-uniformity means that the light originating at the tile center has higher probability to get collected by fibers than the light originating near the tile edge. Thus it clearly depends on the mean light path, which is a function of tile transparency, edge reflection quality and fiber density, and brings parabola-like term to the efficiency. Tile edge coverage serves also to prevent the tile-to-tile light cross-talk.

Local non-uniformity reflects the solid angle from which the fibers are seen from a particular point, and introduces the cosine-like term into the efficiency coordinate dependence. Inter-fiber distance and the fiber diameter affect local non-uniformity.

Following [3] the non-uniformity effect is parameterized with

$$f(x) = a \times \left[1 - A_{global} \cdot \left(\frac{x - x_0}{l_0/2}\right)^2\right] \times \left[1 - A_{local} \cdot \cos\left\{\frac{2\pi}{d} \cdot (x - x_0)\right\}\right] , \qquad (1)$$

where x_0 is a cell center position, l_0 – cell size, d – inter-fiber distance, a – normalization factor, and A_{global} and A_{local} values determine the size of global and local non-uniformity

[2] Modules were constructed of 38 layers of 6 mm thick scintillator tiles alternating with 3 mm thick lead, which corresponds to a total depth of 20 X_0. Tower transverse size was $55.75 \times 55.75\ mm^2$.

effect correspondingly.

To overcome non-uniformity one follows two major approaches. The first one relies on the on-line or off-line corrections using the complete detector information for particular event. The straightforward solution for electrons to refine shower center position is to extrapolate track information known from tracker (energy-momentum information comes from the track curvature in the magnetic field). Iterative procedure could be exploited to improve precision for γ showers. The above formulae for non-uniformity effect $f(x)$ gives the estimate for necessary correction if taking preliminary determined shower center position as x. Corrected shower energy versus coordinate distribution, (ε, x), is used for the next iteration. The situation becomes worse when considering two overlapping showers, which belong to photons from π^0 decay. Contribution from pile-up obscures the picture of showers from neutral particles. Global uniformity corrections do not require precise coordinate knowledge, and are easiest to apply.

Within the second approach, efforts to reduce non-uniformity in advance (i.e. at the stage of calorimeter production) are applied. Improving the reflection efficiency from the tile edges and the choice of fiber density are discussed below.

In order to choose tile edge coverage, that improves light reflection efficiency, tiles [3] with blackened, aluminized and white painted edges were studied, by comparing the response to the ^{90}Sr source at the tile center and close to the tile edge. Light was read out via fibers penetrating the tile similar to ordinary module read-out. Directly measured was the PM current at different ^{90}Sr source positions over the tile surface. Table 1 shows response at the tile center and the difference in response between the center and the edge for tiles with different edge covers, thus comparing global non-uniformity effect and corresponding degradation of the mean light path, induced by tile edge reflection inefficiency. These results agree well with Monte Carlo calculations, which also predict 2, 5 and 7 cm mean light path for blackened, aluminized and white tile edge respectively.

Another impact on the uniformity comes from the fiber density of the module. Reduc-

[3] Tiles of $55.5 \times 55.5\ mm^2$ size were used for this test.

Table 1: *Non-uniformity global effect, induced by tile edge reflection inefficiency. Shown are response at the tile center and the difference in response between the center and the edge of tile for blackened, aluminized and white painted edges. Directly measured was the PM current depending on the* ^{90}Sr *source position over the tile surface*

edge coverage type	response at tile center, $[nA]$	center-edge difference, [%]
blackened	48	19
aluminized	112	7
white diffused (BC-622A)	134	4

ing the fiber density in the outer section module [4] improves global uniformity (tile edge is better seen from the tile center if fiber density is reduced, and is effectively screened from the tile center if fibers are placed denser) and reduces the module cost; at the same time local uniformity degrades (as the distance between fibers increases) and light yield reduces.

Three identical modules of $124.2 \times 124.2\ mm^2$ size [5] were assembled with 64, 100 and 144 fibers per module [6] correspondingly. Tile edges were chemically mat to provide the diffusive reflection, relying on the test results shown above. Aluminum mirror was made on the fiber front ends. Modules were tested with MIPs and 50 GeV electron beam [7] at SPS (Super Proton Synchrotron), CERN. Table 2 summarizes the measurements, shown is the light yield and response non-uniformity effect contribution. Figure 1 shows the response, after global type uniformity correction, versus the coordinate as measured by the coordinate detectors with the e^- beam, the response clearly follows the fiber

[4] Inner section modules suffer from substantial radiation dose, annual dose riches 0.25 $Mrad$ value for the innermost region [4]. To minimize module degradation the geometry absorption length, λ_{geom}, should be as small as possible [4], thus prohibiting the fiber density reducing. On the contrary, dose accumulated by the outer section modules does not exceed 0.02 $Mrad$ per year of LHCb operation, and the fiber density optimization is allowed.

[5] The size presently expected for outer section modules is $121.2 \times 121.2\ mm^2$.

[6] Square of even allows to loop fibers at the module front edge.

[7] Nonet of modules was used for measurements.

Table 2: *Response non-uniformity of modules with* 144, 100 *and* 64 *fibers per module, as measured with MIP and electron beams. Global and local non-uniformity effects are expressed in terms of* A_{global} *and* A_{local} *coefficients from parameterization* (1) *correspondingly. Implied is the integration over the effect along y-direction*

	144 fibers	100 fibers	64 fibers
MIP beam			
light yield, [$a.u.$]	1.20	1.00	0.74
global non-uniformity, A_{global}	0.06(1)	0.03(1)	0.01(1)
local non-uniformity, A_{local}	0.004(1)	0.009(1)	0.012(1)
e^- beam			
light yield, [$a.u.$]	1.27	1.00	0.70
global non-uniformity, A_{global}	0.03(1)	0.02(1)	0.02(1)
local non-uniformity, A_{local}	0.003(1)	0.005(1)	0.007(1)

pattern. According to the expectations non-uniformity effect increases with the inter-fiber distance, the fit gives 0.3%, 0.5% and 0.7% for 144, 100 and 64 fiber modules correspondingly. The 0.7% value obtained for 64 fiber module becomes comparable with the design value for constant term of 0.8%. This is especially critical for photons, where no straightforward correction could be applied. Nonetheless non-uniformity, and in particular local non-uniformity, effect is expected to be strongly smeared when particles come at non-zero angle θ to the normal to calorimeter surface. This angle exceeds $\theta_0 = 80\ mrad$ for photons entering outer region of calorimeter. Monte Carlo estimates show the corresponding suppression of local non-uniformity effect by a factor of 3.

Dedicated Monte Carlo studies of light propagation in the scintillator tile with WLS fibers, illustrate the interplay between the tile transparency and the fiber density impacts on the local uniformity of response. In Table 3 shown is the value of A_{local} coefficient from parameterization (1). Options with 144, 100 and 64 fibers per tile, and mean light path of $\lambda_{Sci} = 15\ cm$, $25\ cm$ and $50\ cm$ are considered. Not only fiber

Table 3: *Scintillator transparency and fiber density impact on the local uniformity of the response to MIPs, as studied with Monte Carlo. Shown is the value of* A_{local} *coefficient from parameterization* (1). *Options with* 144, 100 *and* 64, *and* $\lambda_{Sci} = 15$ *cm*, 25 *cm and* 50 *cm are considered*

	Fibers per tile		
Mean light path, λ_{Sci}	144	100	64
15 *cm*	0.0035(5)	0.0091(4)	0.0132(3)
25 *cm*	0.0005(5)	0.0051(4)	0.0089(3)
50 *cm*	0.0004(4)	0.0022(3)	0.0063(3)

density increasing, but also the increasing of mean light path improves local uniformity of response. Indeed, if photons walk long enough in the tile (due to good scintillator transparency and efficient edge reflection), they meet fiber anyway, and local non-uniformity becomes small. The picture obtained is in good agreement with the local uniformity as measured with MIPs (see Table 2), if assuming $\lambda_{Sci} \approx 15$ *cm*.

As shown by our measurements $\sim 30\%$ of light is reflected from white paper (TYVEK) prior to being collected by WLS fibers. Therefore uniformity of response can be complementary improved by using masks – paper placed between tile and TYVEK, governing the reflection from tile sides. Mask suppresses the light at x corresponding to $f(x)$ maxima (see (1)), thus improving the uniformity of both types.

In conclusion, accepted is the solution with 64 fibers per outer section module, which improves global uniformity and reduces the module cost. Additionally this solution leads to smaller size fiber bundle, and thus moderates the requirements to the photocathode uniformity. Matting of tile edges improves light collection, global uniformity and prevents tile-to-tile crosstalk. Alternatively the tile edges could be aluminized (HERA-B -like solution) with the technique of Al evaporation in vacuum by HV-induced explosion (reflection quality is $\sim 10\%$ worse). Using masks could further improve both (global and local) types of uniformity.

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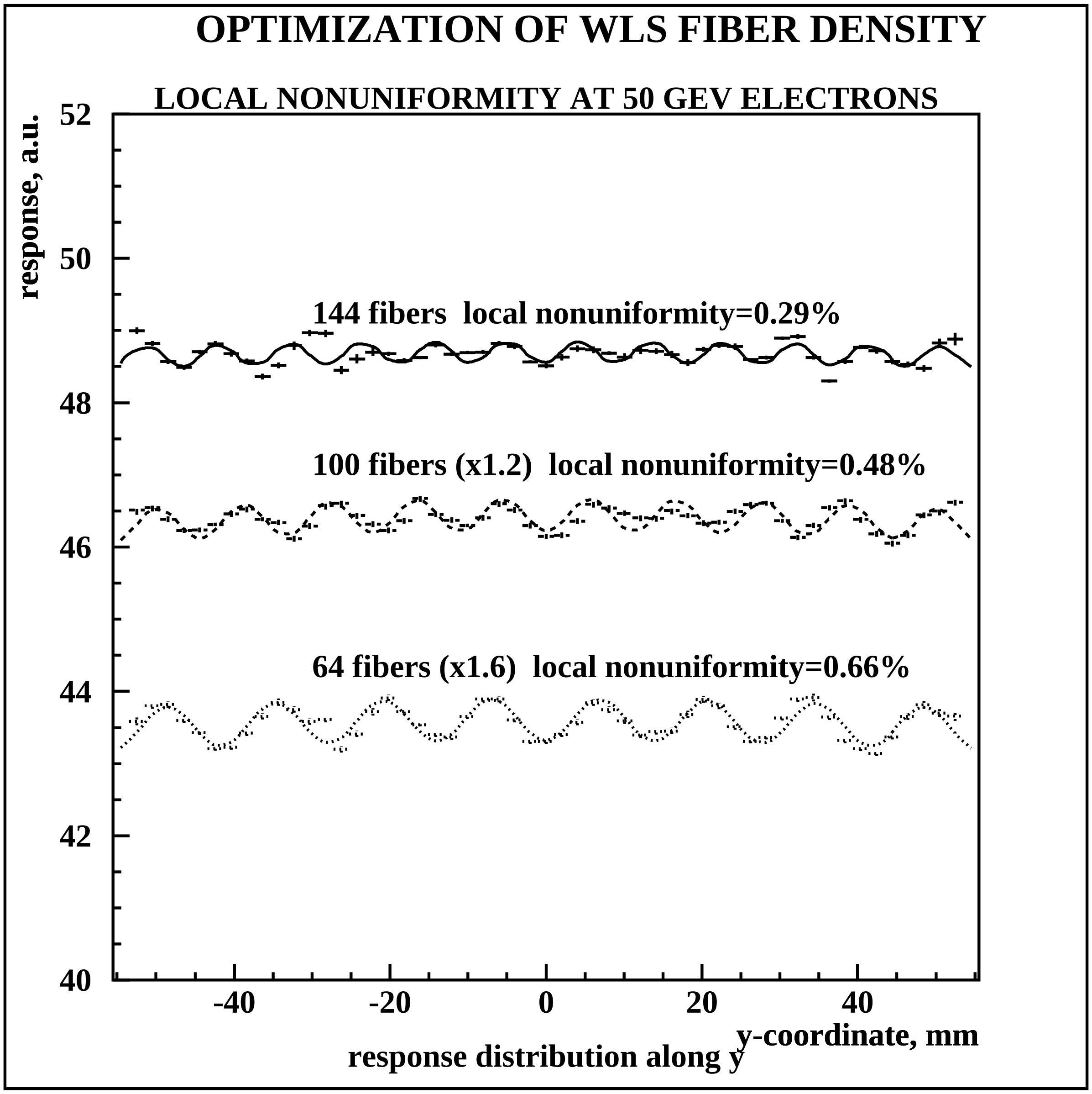

Figure 1: *Local response uniformity measured for three modules with* 64, 100 *and* 144 *fibers per module correspondingly, with* 50 *GeV electrons at X*7 *beam at CERN. Global type uniformity corrections are taken into account on the plot. The curves are the results of the fit*