Paper presented at “SCINT'99”, Moscow, 16–20 August 1999.

Light collection in the CMS lead tungstate crystals : relation between monitoring and calibration variations

R. Chipaux

CEA/DSM/DAPNIA/SED, CE-Saclay, 91191 Gif sur Yvette cedex, France

Abstract

The ageing of scintillating crystals under radiation leads to a deterioration of their transparency, thus of their effective light yield and their calibration. The link between the transparency variation, as measured by a fibre optic monitoring system, and the calibration variation is not trivial.

A model describing the light collection process is proposed. It helps to understand the parameters, which govern this correlation, mainly absorption length and light back-reflection or diffusion characteristics. This model describes well the results of numerical qualitative simulations of light collection in lead tungstate crystals. It also explains the differences between calibration and monitoring variations observed in test beam.

Important slopes could be obtained when the crystal ends have a different behaviour for monitoring and scintillation lights, like in the case of bare surfaces. As anticipated, the correlation slope tends toward one, when absorption is low and both monitoring and scintillation lights are well contained in the crystal, and thus independently of the geometry (front or back) of the monitoring light injection.

Keywords : Scintillator detector, light yield, ageing, ray tracing.

1. Introduction

In scintillation detectors exposed to radiation, like in the CMS lead tungstate electromagnetic calorimeter [1], the light collection efficiency will vary along time, because of the modification of the scintillating material transparency. In CMS, for example, maintaining the energy resolution of the instrument will require : – a calibration with physical events of known energy, at a time scale of a few weeks ; – a continuous monitoring of the optical properties of the crystals by a fibre optic monitoring system, to interpolate calibration corrections during that time [2]. However, the correlation between variation of crystal transparency, as measured by the monitoring system, and variation of the calibration parameters of the same crystal is not trivial [2].

We have proposed a model describing the light collection process in transparent materials. This model is detailed in [3] and we will focus here on its main qualitative results, namely on the correlation monitoring/calibration.

2. Modelisation and simulation

We recall here the main results of the model. See [3] for details. Both monitoring and scintillation lights can be decomposed in a direct part, coming directly to the photodetector, (indexed *d*), a “back” part (for scintillation light), (indexed *b*) and a “multiple turn” part. The variation of monitoring and scintillating light yield efficiencies (respectively $C_m(t, l)$ and

$C_s(t, l, z)$) can be expressed as function of a few numbers of parameters, namely the optical absorption coefficient $\mu(t, l)$, effective reflection coefficients k (respectively k_m and k_s), and effective path coefficients b. In the model, the effect of light absorption in the material, represented by $\mu(t, l)$, is disconnected from other sources of light loss, which are associated to the coefficients k.

With these hypothesis, the light collection efficiency for monitoring light, $C_m(t, l)$, can be written as :

$$C_m(t, l) = \frac{C_{m_D} \exp\left(-b_{m_d} \mu(t, l) L\right)}{1 - k_m^2 \exp\left(-2 b_m \mu(t, l) L\right)} \tag{1}$$

where L is the length of the scintillator.

In case of monitoring light is injected from the back of the crystal, *i.e.* from the side of the photo detector, $2\,b_m$ should naturally replace b_m in this equation.

And the efficiency for scintillation light, $C_s(t, l, z)$, can be written as :

$$C_s(t, l, z) = \frac{C_{s_D} \exp\left(-b_{s_d} \mu(t, l)(L - z)\right) + C_{s_B} \exp\left(-b_{s_b} \mu(t, l)(L + z)\right)}{1 - k_s^2 \exp\left(-2 b_s \mu(t, l) L\right)} \tag{2}$$

As shown in [3], this model agrees with the simulations performed assuming perfectly polished materials. For a "uniformized" scintillator, *i.e.* for a scintillation detector in which the light yield has been voluntary homogenised in z, (for example by depolishing one lateral face, as foreseen in the CMS calorimeter), one can nevertheless presume that the same arguments can be used. In that case, the effective reflection coefficients k would represents the global result of end and lateral surfaces reflections, or more generally the quality of light confinement in the crystal.

To obtain the variation of the detector calibration coefficients $S_s(t, E_0)$, $C_s(t, l, z)$ should be convoluted with the energy density and the photodetector quantum efficiency, and then integrated over z and λ. (One assumes that other elements, such as quantum efficiency, gain, etc. are constant). For small variations, (*i.e.* low induced absorption), it is reasonable to write the total scintillation efficiency by the same equation using mean parameters : $\bar{\mu}$ (absorption coefficient at the wavelength of the effective maximum of emission) and $\bar{z}_{sh}$ (mean position of the energy deposited) :

$$S_s(t) = \frac{S_{s_D} \exp\left(-{}^{sh}b_{s_d} \bar{\mu}(t)(L - \bar{z}_{sh})\right) + S_{s_B} \exp\left(-{}^{sh}b_{s_b} \bar{\mu}(t)(L + \bar{z}_{sh})\right)}{1 - {}^{sh}k_s^2 \exp\left(-2\,{}^{sh}b_s \bar{\mu}(t) L\right)} \tag{3}$$

3. Correlation

In high absorption materials, *i.e.* when $\mu^{-1}(t, l) = \Lambda(t, l) \leq L^2$, the relative variations of the efficiencies $(\mathrm{d}S_m / (S_m\,\mathrm{d}\mu)$ and $\mathrm{d}S_s / (S_s\,\mathrm{d}\mu))$, (and thus the correlation slope $(\mathrm{d}S_s / S_s) / (\mathrm{d}S_m / S_m)$, which is the parameter that will be used to correct the calibration

coefficients from the monitoring data), are governed by the direct light variation, so by the effective paths : $b_{m_d} L$ and $b_{s_d}\left(L-\bar{z}_{sh}\right)$. b_{m_d} is related to the angular aperture of the optic fibre injecting the monitoring light ; b_{s_d} is related to the angular aperture of the photodetector. They are close together, and the main difference comes from the two lengths L and $L-\bar{z}_{sh}$. The correlation slope is given by $b_{s_d}\left(L-\bar{z}_{sh}\right)/b_{m_d} L$.

On the contrary, in low absorption materials the effective reflection parameters k_m and k_s play a crucial role. If the containment is poor for both types of light, (k_m and k_s near 0), the correlation slope remains equal to $b_{s_d}\left(L-\bar{z}_{sh}\right)/b_{m_d} L$, as shown in figure 1 for scintillator's absorbing ends. If the containment is efficient, (k_m and k_s near 1), the relative variations tend to equilibrate, and the correlation slope approaches 1. This is the case in figure 1 for reflective and diffusive ends. In these conditions, the geometry of monitoring light injection (from the front or the back of the scintillator) is relatively secondary.

They are cases for which a notable difference exists in containment between scintillation light and monitoring light. In the very simple example of bare polished materials, the monitoring light is only partially reflected at the detector's ends, when part of the scintillation light is in total reflection on every surfaces including ends (obviously at the exception, to be able to be detected, of the photodetector surface). This induces high correlation slope. It can reach 2, 3 or even more, as shown in figure 1 for refractive ends. This could explain, at least qualitatively, the values of slope observed in test beam, and their dispersion [4]. As seen in the figure, the slope is very sensitive to the initial absorption length, or correlatively, to the quality of the light confinement, and both parameters can vary sensibly among the crystals tested.

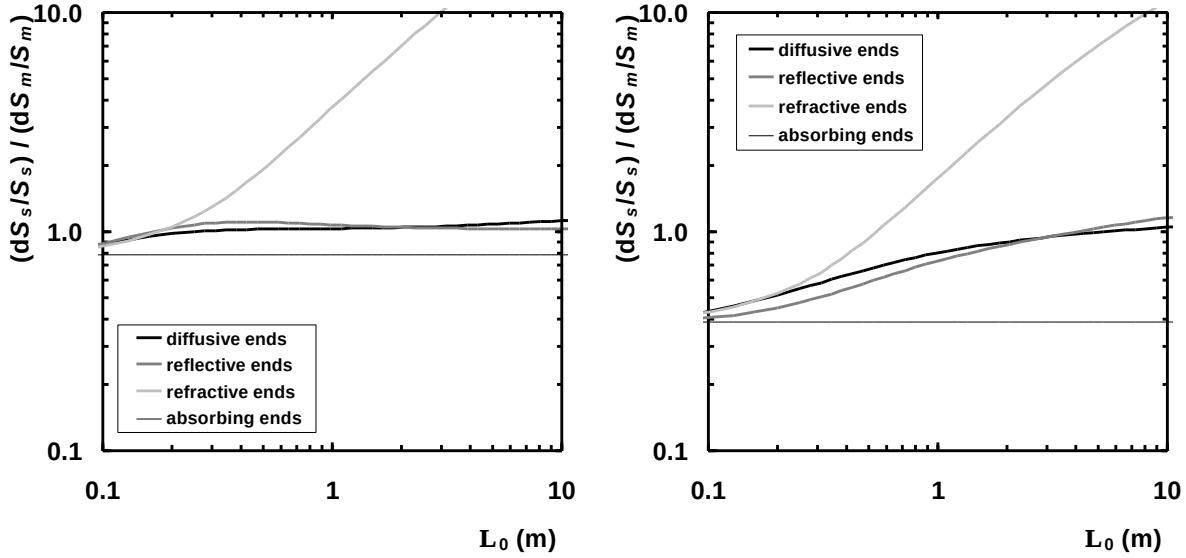

Figure 1 : Variation of the slope of the correlation between scintillation light and monitoring light variations (*i.e.* $\left(\mathrm{d}S_s/S_s\right)/\left(\mathrm{d}S_m/S_m\right)\big|_{\Lambda=\Lambda_0}$) as a function of the initial absorption length Λ_0., for various types of treatment of the scintillator's ends : fully absorbing ; bare (refractive) ; covered by a perfect specular reflector (reflective) or by a perfect diffuser (diffusive).
Simulations have been made for a 50 GeV electron shower in a tapered crystal with perfect surfaces (without chamfers), assuming the same absorption variation for scintillation and monitoring lights.
On right, monitoring light is injected through the front of the scintillator (CMS ECAL geometry), on left through the back.

4. Conclusion

This model, based on a limited number of parameters related to physical quantities – absorption length, mean path lengths, reflection transmission (or light confinement) coefficients –, points out the two regimes for scintillation/monitoring correlation. In high absorption materials, the signals are due to the direct light, and the correlation will be dominated by the difference of the optical path lengths. We may predict in that case values of correlation slope less than one, because of the longer path for the monitoring light. In low absorption materials, an increase of absorption affects overall the indirect light, and the correlation is dominated by the quality of light containment, and by its eventual difference between monitoring and scintillation lights. This may lead to important correlation slopes, especially in bare, polished, materials. In order to keep the slope near the optimal value of one, highly reflexive, either diffusive or specular, coatings should be used. This not only increases the light yields, but also should uniformize their relative variations.

Acknowledgements

This work was in the frame of the CMS ECAL monitoring development project, under the head and with the constant support of J.-P. Pansart and J. Rander.

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