Dual-readout Calorimetry with Scintillating Crystals

Davide Pinci\textsuperscript{a} on behalf of the DREAM collaboration

\textsuperscript{a}INFN, Sezione di Roma, Italy.

The possibility of evaluating the amount of the energy released by the electromagnetic part of a hadronic shower ($f$) would allow to account for one of the main sources of the fluctuation of the hadronic calorimeter response. The dual-readout method allows an event-by-event measurement of $f$, as it was originally demonstrated with the DREAM sampling hadronic calorimeter. This approach can be extended to homogeneous detectors like crystals if Cherenkov and scintillation light can be separated by exploiting their main properties. In this paper we present several methods developed for distinguishing the two components in PWO and BGO crystal based calorimeters and the results obtained.

1. Introduction

The dual-readout approach, which allows an event-by-event measurement of the electromagnetic shower fraction ($f$), was originally demonstrated with the DREAM hadronic calorimeter [1]. It gives the possibility of upgrading the performance of a hadronic calorimeter by reducing one of the main sources of the response fluctuation. Suppose to have a calorimeter equipped with two sensitive media. For example a medium sensitive to the Cherenkov light and a medium sensitive to the Scintillation light with different response ratios to the hadronic and electromagnetic component of the shower ($h/e$). After a suitable calibration, the responses provided by the two parts of the calorimeter to a hadronic shower are:

$$C = [f + c(1 - f)]E$$

(1)

where $c = (h/e)c$.

$$S = [f + s(1 - f)]E$$

(2)

where $s = (h/e)s$.

On a event-by-event basis, once $c$ and $s$ are known, it is possible to evaluate the electromagnetic fraction $f$ by simply measuring the $C/S$ ratio:

$$f = \frac{c - s(C/S)}{(C/S)(1 - s) - (1 - c)}$$

(3)

and the energy $E$ released in the calorimeter by the shower, automatically corrected for value of $f$, is

$$E = \frac{S - \lambda C}{1 - \lambda}$$

(4)

where the $\lambda$ parameter is:

$$\lambda = \frac{1 - s}{1 - c}$$

(5)

and it is a “constant” of the calorimeter. Starting from the relation:

$$S = (1 - \lambda)E + \lambda C$$

(6)

on a hadron beam of fixed energy $E$, the $\lambda$ parameter and the beam energy can both be easily obtained from the linear fit of $S$ as a function of $C$.

2. Dual readout method with scintillating crystals

One very promising application of the dual readout calorimetry technique is represented by the DREAM hadronic calorimeter [1]. The main limitation of such a detector is represented by the low Cherenkov photo-electron production (8 ph.e. per deposited GeV). This number arises from the very small sampling fraction and leads to limited performance on electromagnetic showers.
Table 1
Main properties of the BGO and PWO.

<table>
<thead>
<tr>
<th>Material</th>
<th>Scint. light-yield</th>
<th>Scint. decay time (ns)</th>
<th>Scint. spectrum peak (nm)</th>
<th>Transparency cut-off (nm)</th>
<th>Refr. index</th>
<th>Density g/cm(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGO</td>
<td>20.0</td>
<td>300</td>
<td>480</td>
<td>320</td>
<td>2.15</td>
<td>7.13</td>
</tr>
<tr>
<td>PWO</td>
<td>0.3</td>
<td>10</td>
<td>420</td>
<td>350</td>
<td>2.30</td>
<td>8.28</td>
</tr>
</tbody>
</table>

One idea to increase the number of Cherenkov photo-electrons and to improve the performance on electromagnetic showers is to exploit the dual readout method with a homogeneous material. In recent papers ([2], [3]) it was demonstrated the possibility of separating, in a homogeneous scintillating material, the Cherenkov and scintillation components of the total light yield by exploiting their differences in timing properties, directionality and emission spectrum. Two scintillating materials, the PWO and the BGO were tested, with high energy particle beams, in 2006, 2007 and 2008. Their main properties are reported in table 1. For both materials a complete calorimeter system was built with an electromagnetic section based on scintillating crystals and a hadronic section made by the DREAM detector as shown in fig. 1.

Figure 1. Set-up used for testing the PWO (top) and the BGO crystals (bottom).

The PWO-based calorimeter was made by a matrix of 19 crystals, parallel to the beam and readout on the two lateral faces by two fast and low-gain photo-multipliers. In the BGO measurements only one crystal was used, placed parallel to the beam and readout on the two small faces. Between the BGO crystal and the photo-multipliers two optical filters were inserted: a “yellow” filter transparent to the long wavelengths and a “UV” filter transparent to the short wavelengths. The yellow filter transmitted the scintillation light emitted by the crystal and the “UV” one allowed the transmission of the Cherenkov light while attenuating the scintillation light.

In all measurements, the shape of the signals provided by the photo-multipliers were acquired by means of a 5 GS/s oscilloscope. In order to get information on the amount of Cherenkov light produced in each event two different methods were used for the two materials:

- For the PWO the ratio between the charge integrated in the first 6.4 ns and the total one (qRatio) was calculated event by event (see fig. 2). As it is shown in fig. 3 the events with a large qRatio (right) show, a high prompt peak, due to a high amount of Cherenkov light produced. The behavior of the trailing edge, excluding the oscillating pattern due to internal reflections of the Cherenkov light, was fitted in both cases to an exponential decay with a time constant of 10 ns.

- For the BGO the waveform provided by the PMT placed downstream of the UV filter was off-line integrated in two different gates (see fig. 4):
  1. \(C\) around the Cherenkov peak;
  2. \(S\) in the exponential tail.
The analysis of the signal on the side equipped with the “yellow” filter allowed the evaluation and the subtraction of the contamination of the scintillation light in the \( C \).

3. Results

In a hadronic shower, the electromagnetic components produced late in the ECAL, will be absorbed by the HCAL. This effect gives rise to a correlation between the electromagnetic fraction measured by the ECAL and the one measured in HCAL. By using the qRatio for the PWO and the C/S ratio for the BGO, the value of \( f \) could be evaluated event by event. For a fixed released-energy value (fig. 5), a large value of \( f \) in the shower produces:

- a high scintillation signal;
- a small fractional width in the Dream response because of the lower fluctuations induced by the invisible energy of the non-electromagnetic fraction;

Moreover, as it is shown in fig. 6, events with different \( f \) measured in the ECAL have a different response distribution in the hadronic calorimeter. By choosing events with different values of \( f \) in the ECAL it is possible to select different “sub-distributions” in the HCAL scintillating fibres response that are narrower than the global one.

A crystal-based ECAL is able to give precious information on the electromagnetic content of the shower and to allow to correct the HCAL response.
4. Conclusion

The separation of Cherenkov and scintillation components in the signals produced by homogeneous scintillating material was demonstrated to be feasible. This feature gives the possibility of evaluating the electromagnetic fraction of a shower allowing to reduce part of the fluctuations and non-linearities in measuring the Energy released by a hadron. The application of the Dual-Readout method also to the electromagnetic section can be exploited to improve the global performance to electron and pion showers.

REFERENCES


Figure 5. Fractional widths (a) and mean values (b) of the scintillating fibres response distribution in DREAM as a function of the C/S ratio in the PWO-ECAL (top) and in the BGO-ECAL (bottom).

Figure 6. Different “sub-distributions” of the HCAL scintillating fibres response for events with different values of $f$ measured in BGO-ECAL (top) and PWO-ECAL (bottom).