Dual-readout Calorimetry with Scintillating Crystals

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Abstract. The dual-readout approach, which allows an event-by-event measurement of the electromagnetic shower fraction, was originally demonstrated with the DREAM sampling calorimeter. This approach can be extended to homogeneous detectors like crystals if Cherenkov and scintillation light can be separated. In this paper we present several methods we developed for distinguishing the two components in PWO and BGO based calorimeters and the results obtained.

1. Introduction
The possibility of evaluating the amount of the energy released by the electromagnetic part of a hadronic shower (the so called electromagnetic fraction $f$) would allow to account for one of the main sources of the hadronic calorimetry 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 components of the shower ($h/e$). After a suitable calibration, the responses provided by the two parts of the calorimeter to a hadronic shower are:

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

where $c = (h/e)_C$ and $s = (h/e)_S$.

On a event-by-event basis, by simply measuring the $C/S$ ratio, it is possible to evaluate the electromagnetic fraction $f$ as:

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

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

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

where the $\lambda$ parameter is:

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

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

$$S = (1 - \lambda)E_0 + \lambda C$$

on a hadron beam of fixed energy $E_0$, the $\lambda$ parameter and the beam energy can both be easily obtained from the linear fit of $S$ as a function of $C$.
Table 1. Main properties of the BGO and PWO.

| Material | Scint. light-yield |
|----------|-------------------|
|          | NaI(Tl) %          |
| BGO      | 20.0              |
| PWO      | 0.3               |

|                  | Scint. decay time (ns) | Scint. spectrum peak (nm) | Transparency cut-off (nm) | Refr. index | Density g/cm$^3$ |
|------------------|------------------------|---------------------------|---------------------------|-------------|-----------------|
| BGO              | 300                    | 480                       | 320                       | 2.15        | 7.13            |
| PWO              | 10                     | 420                       | 350                       | 2.30        | 8.28            |

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 it leads to limited performance on electromagnetic showers. 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 paper ([2]) it was demonstrated the possibility of separating, in a homogeneous scintillating material, the Cherenkov and Scintillation components to 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 beam, in 2006 and 2007. Their main properties are reported in table 1. For both the 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. The PWO-based calorimeter was made by a matrix of 19 crystals, 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, while the “UV” one allowed only the transmission of the Cherenkov 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 asymmetry \((B-A)/(B+A)\) of the light collected by the two PMTs with the matrix rotated at 63° with respect to the beam was evaluated. In this configuration the Cherenkov light \((C)\) reached only the B PMT while the Scintillation one \((S)\) was collected by both the PMTs. It results:

\[
\frac{B - A}{B + A} = \frac{C}{C + 2S}
\]

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

![Figure 2](image)

**Figure 2.** Analysis performed off-line on the “UV-side” signals.

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 formula 3. In fig. 3 the electromagnetic fraction measured in the ECAL and HCAL by means of the above methods are reported.

![Figure 3](image)

**Figure 3.** Electromagnetic fraction measured in a section of the calorimeter system as a function of the one measured in the other section for the PWO (left) and the BGO crystals (right).
In particular, for the BGO case, the response of the scintillator fibers in Dream was analyzed as a function of the C/S ratio. For a fixed released-energy value (fig. 4), 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;

![Image](image.png)

**Figure 4.** Fractional widths (left) and mean values (right) of the scintillator response distribution in DREAM as a function of the C/S ratio in the BGO-ECAL.

Moreover, as it is shown in fig. 5, events with different $f$ measured in the ECAL have a different distribution in the calorimeter. By choosing events with different values of $f$ in the ECAL it is possible to select different “sub-distributions” in the HCAL scintillator 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 Čerenkov 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
[1] N. Akchurin et al., “Hadron and jet detection with dual-readout calorimeter”, Nucl. Instr. and Meth. A 537 (2005) 537.
[2] N. Akchurin et al., “Contributions of Čerenkov light to the signals from lead tungstate crystals”, Nucl. Instr. and Meth. A 582 (2007) 474.
[3] N. Akchurin et al., “Dual-readout calorimetry with lead tungstate crystals”, Nucl. Instr. and Meth. A. 584 (2008) 273.
Figure 5. For both the PWO (top) and BGO (bottom) crystals, events with different values of $f$ in ECAL have different “sub-distributions” in the HCAL scintillator response that are narrower than the global one.