Dual-Readout Calorimetry with Crystals

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***Abstract*—Analysis of the signals generated by high-energy particles in lead tungstate crystals shows that a significant fraction (up to 20%) of the light generated in these crystals is not the result of scintillation processes, but rather of the Cherenkov mechanism. We have explored this phenomenon with the purpose to improve the characteristics of hadron calorimeters. A small electromagnetic calorimeter consisting of lead tungstate crystals was exposed to 50 GeV electrons and pions. This calorimeter was backed up by the DREAM Dual-Readout Calorimeter, which measures the scintillating and Cherenkov light produced in the shower development, using two *different* media. The signals from the crystal calorimeter were analyzed in great details in an attempt to determine the contributions from these two types of light to the signals, event by event. This information makes it possible to eliminate the dominating source of fluctuations and thus achieve an important improvement in hadronic calorimeter performance. Preliminary results on the dual-readout of a BGO crystals are also reported.**

I. Introduction

THE energy resolution of calorimeters is determined by fluctuations. If one wants to improve that resolution significantly, then one has to address the dominating source of these fluctuations. In almost all calorimeters, fluctuations in the electromagnetic shower fraction (f_{em}) dominate the energy resolution for hadrons and jets. These fluctuations, and their energy-dependent characteristics, are also responsible for other undesirable calorimeter characteristics, in particular hadronic signal non-linearity and a non-Gaussian response function. There are two possible approaches to eliminate the effects of these fluctuations: By designing the calorimeter such that the response to electromagnetic (em) and non-em energy deposit is the same, the so-called compensated calorimeters, or by measuring the em shower fraction event-by-event. The latter approach is chosen in the DREAM (Dual-REAdout Method) project, where we have shown that the value of f_{em} can be measured event-by-event by comparing the signals from two independent active media (scintillating and quartz optical fibres), which measure respectively the amount of scintillating and Cherenkov light produced in the absorption process [1].

The elimination of this dominant source of fluctuations means that other types of fluctuations now dominate the detector performances, and further improvements may be obtained by concentrating on these. Apart from the trivial effects of fluctuations in side leakage, which are automatically eliminated in sufficiently large instruments, the energy resolution of the DREAM calorimeter is limited by fluctuations in the Cherenkov light yield and by sampling fluctuations. For example, the small Cherenkov light yield (8 photoelectrons per GeV) contributed more than $35\%/\sqrt{E}$ to the measured hadronic energy resolution.

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There is absolutely no reason why the DREAM principles should be limited to fiber calorimeters. In particular, they could be applied to homogenous detectors, provided that a way is found to distinguish the Cherenkov and scintillation light produced by such a detector. The use of a homogenous material will largely increase the number of Cherenkov photoelectrons produced, and will improve the calorimeter performance on electromagnetic showers. In the following we report on the studies we performed with $PbWO_4$ and BGO crystals.

II. Evidence of Cherenkov light production in $PbWO_4$ crystals

To evaluate the fraction of signal due to Cherenkov radiation in a scintillating crystal we used a single $PbWO_4$ crystal (18 cm long and 2.2 cm by 2.2 cm in cross section) equipped with two photomultipliers (PMs), one at each end. This setup was exposed to a 10 GeV electron beam from CERN SPS and we acquired the time structure of the signals from the two PMs by means of waveform digitizers.

Evidence of a Cherenkov component in the signal [2] was found by exploiting the directionality of the Cherenkov light production. Cherenkov light is emitted at an angle $\theta_c = \arccos(1/\beta n)$ (θ_c is close to 63° for this crystal) with respect to the charged particle direction. The Cherenkov light exiting the crystal - and seen by the photomultiplier - is maximized when the crystal is tilted by an angle $\theta = 90 - \theta_c$ with respect to the beam line (see figure 1 for the definition of θ). The asymmetry $(R-L)/(R+L)$ of the signal amplitudes R and L recorded respectively by the right and the left PMs as a function of the tilt angle is shown in figure 1. From the maximum value of the asymmetry we estimated the amount of Cherenkov light contributing to the total signal, corresponding to at least 13%. Showers in a later development stage, obtained by placing a $7X_0$ lead block in front of the crystal, show a smaller asymmetry. This is due to the increase of the isotropic component of the particles generating Cherenkov light, thus reducing the correlation between the beam line and the crystal axis directions.

The asymmetry distribution recorded at $\theta = 27°$ is shown in figure 2. This distribution has a relative width exceeding 40%, dominated by photoelectron statistics (electrons deposit only 0.3 GeV in the crystal).

III. Results from a $PbWO_4$ crystal matrix

We have seen that the directionality of the light can be used to estimate the amount of Cherenkov light produced in the crystal. To evaluate how this could be used to improve the overall calorimeter response to hadronic showers we built a crystal matrix composed of 19 $PbWO_4$ crystals, 18 cm long and 2.2 cm by 2.2 cm in cross-section, and we read it out by

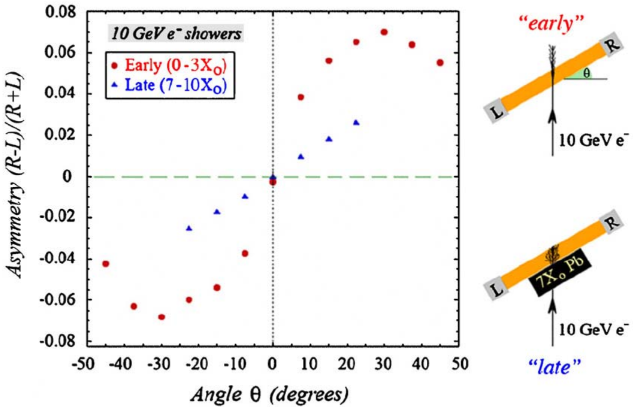

Fig. 1. Signal asymmetry as a function of the crystal angle θ with respect to the beam line (from [2]).

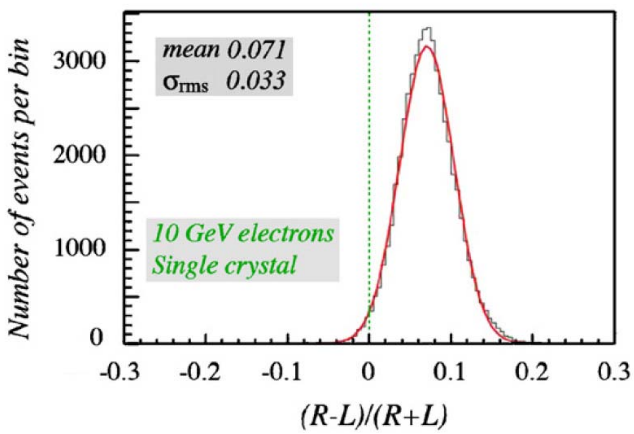

Fig. 2. Signal asymmetry distribution seen at $\theta = 27°$ (from [2]).

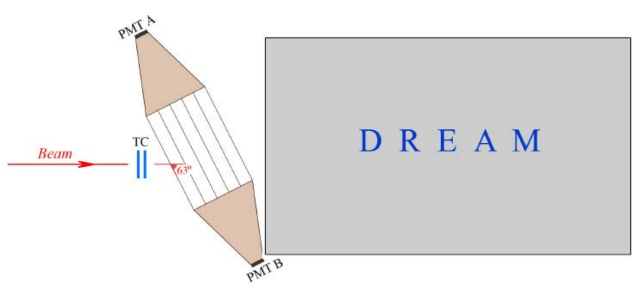

Fig. 3. The $PbWO_4$ matrix in front of the DREAM calorimeter. The crystal matrix is tilted at an angle $\theta = 90 - \theta_c$ with respect to the beam normal incidence to estimate the fraction of Cherenkov light produced.

means of two R5900U Hamamatsu PMs through mylar cone-shaped air light-guides. The crystal matrix was placed in front of the DREAM calorimeter (see figure 3) with the purpose of evaluating their combined performance [3]. To assess the performance of the dual-readout method on the $PbWO_4$ crystal matrix a beam of 100 GeV negative pions was used. For every hadron starting its showering in the crystal matrix we calculated the left-right signal asymmetry, shown in figure 4c. We then selected events with asymmetries in the lower and the upper tail of the distribution and we histogrammed their total

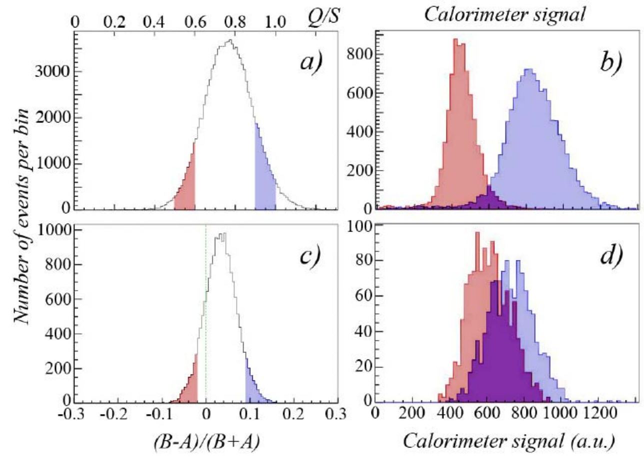

Fig. 4. (a) Q/S ratio for 100 GeV negative pions in standalone DREAM. The energy distributions of the events in the lower and upper tails of the Q/S distribution are shown in (b). Figure (c) showns the left-right asymmetry for the BGO crystal matrix + DREAM for 100 GeV negative pions. The energy distributions of the events in the lower and upper tails of the asymmetry distribution are shown in (d). This is the proof of principle that the dual-readout method works for $PbWO_4$ homogenous calorimeters. Results are from [3].

energy deposit in the crystal and DREAM calorimeters, as it is shown in figure 4d. The two energy distributions peak at two different values, and their individual widths are smaller than the width of the total energy distribution. Figure 4d can be compared with figure 4b, where we histogrammed the energy distribution in the standalone DREAM calorimeter for two different intervals of Q/S (figure 4a): It is clear from the much larger separation of the two energy distributions that Q/S is a better estimator of the Cherenkov fraction of the signal. Figure 4d is indeed the proof of principle that the dual-readout method works on the $PbWO_4$ crystal [1], however with some limitations, mainly due to the fact that the estimate of the Cherenkov component by means of the asymmetry is not an optimal method: The measured asymmetry is in general a very small quantity, and also full-contained showers have an asymmetry smaller than minimum ionizing particles.

IV. Choosing the Crystal

The separation of the scintillating and the Cherenkov light components in homogeneous materials can be optimized by taking into account the properties of the Cherenkov and the scintillating light:

Time Response: The Cherenkov light produces a prompt signal, while the scintillation light has an exponential decay in time;

Light Spectrum: Cherenkov spectrum has a $1/\lambda^2$ distribution, while the scintillation light is usually peaked around some well defined wavelength;

Directionality: Cherenkov light is emitted on a cone around the charged particle direction, while scintillation is isotropic;

Polarization: The Cherenkov radiation is linearly polarized.

Based on the above criteria, some qualitative indications can be given for the choice of the homogeneous material. First, the use of a "slow" scintillator would be preferred, to allow the separation of the prompt (Cherenkov) and the delayed (scintillation) component from the signal waveform. The prompt signal timing will usually be dominated by the photodetector response function, so one would take advantage of a scintillator with a decay time much larger than this value, time constants of the order of $20 \div 50$ ns (or longer) would be preferred. Two considerations can then be made to take advantage of the different light spectra. Cherenkov radiation is distributed as $1/\lambda^2$, however it is in general difficult in a standard setup to collect light below 300 nm. For this reason one would like to have a scintillator emitting mainly above 400 nm, in order to dedicate the interval $300 \div 400$ nm of photodetector sensitivity to the Cherenkov light. In this situation the use of colored filters in front of the photomultipliers will allow an efficient separation of the two light components. It should also be noted that the transmittance of the crystal below the scintillation emission peak should be guaranteed for this method to work, otherwise no separation could be achieved based on the light wavelength. This is not easy to obtain in doped crystals, where usually the emission spectrum is partially overlapping the absorption spectrum. Some natural scintillating crystals however have this property. Finally, it should be noted that the scintillation and Cherenkov signals should be comparable at the photodetector, since the corrected calorimeter energy resolution, calculated using both signals, will be dominated by the statistical fluctuations of the smaller signal component.

V. Testing the dual-readout method on a single BGO crystal

All these considerations led us to choose a BGO crystal for our studies. BGO has the following properties:

- Its light emission is peaked at 480 nm (green);
- The crystal is transparent to light down to about 320 nm;
- Scintillation has a 300 ns decay time;
- It has a density of 7.13 g/cm^2, which allows the construction of compact calorimeters.

BGO crystals of 24 cm in length and approximately 3 cm by 3 cm in cross section were available from the L3 endcap electromagnetic calorimeter.

We equipped both ends of a single BGO crystal with a different optical filter to select the scintillation component (S) on one side (yellow low pass filter GG495 [4]) and the Cherenkov component (C) on the other (UV bandpass filter UG11 [5]). The filtered light was readout by means of two Hamamatsu R1355 PMs. In the following we will limit our analysis to waveforms recorded by the so-called "C" photomultiplier.

Figure 5 shows the average waveforms recorded for 50 GeV electrons crossing the BGO crystal, with the crystal tilted at $\theta = 27°$ (black) and at $\theta = -27°$ (red) with respect to the beam line. There is a clear evidence of an excess of prompt light production in one of the two angular positions. It is also important to note that a residual scintillation tail exist below the prompt peak.

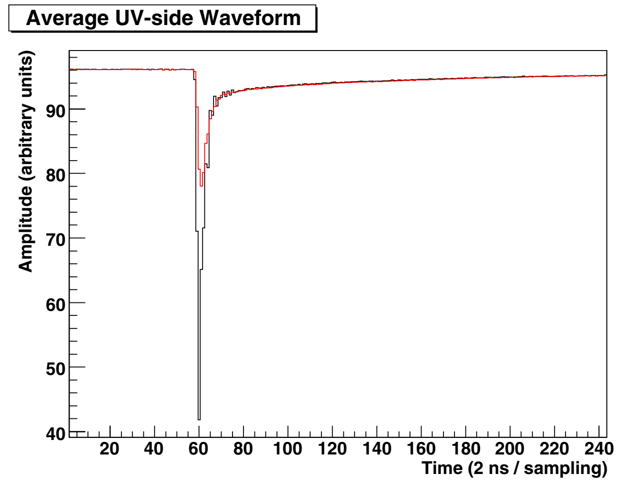

Fig. 5. Average waveforms recorded on photomultiplier C for 50 GeV electrons crossing the BGO crystal, when the crystal is tilted at $\theta = 27°$ (black) and at $\theta = -27°$ (red) with respect to the beam line.

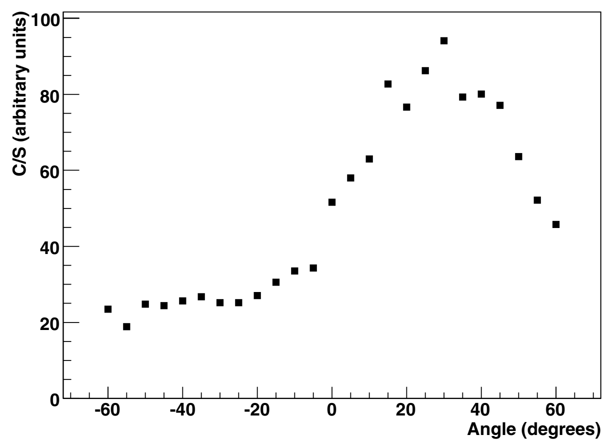

Fig. 6. C/S ratio (in arbitrary units) as a function of the crystal tilt angle with respect to the beam line. The maximum of C/S is indeed in the expected position close to θ_c.

Even if a complete rejection of the scintillation light after the UG11 filter is not achieved (due to the large amount of scintillation light produced in the crystal and the partial overlapping of the BGO emission spectrum and the UG11 filter bandwidth), the filter reduces the two light components to a comparable level and the C to S separation can be achieved event by event by taking into account the time structure of the signal. The scintillation signal S can be estimated from the signal exponential tail, while the Cherenkov signal C can be obtained from the prompt peak amplitude after the tail substraction.

The C/S ratio as a function of the crystal tilt angle is shown in figure 6. There is a clear excess of C/S at angles where the Cherenkov light can easily reach the C photomultiplier. This indicates qualitatively that the separation of the two light components has been efficiently performed.

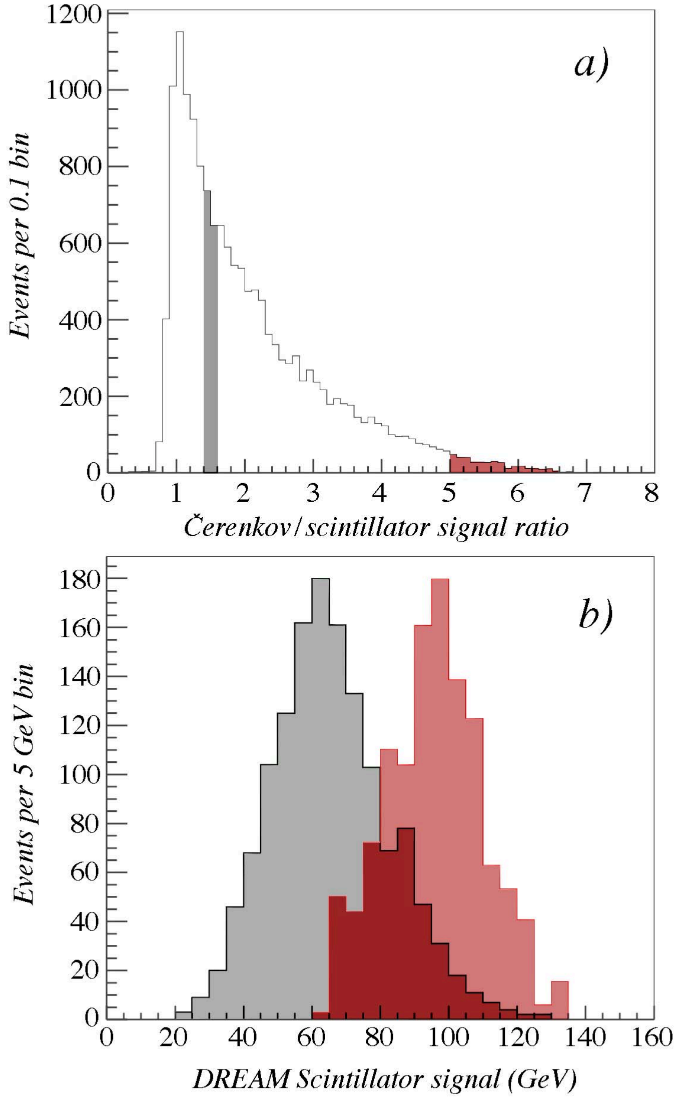

Fig. 7. (a) Distribution of C/S values measured in the BGO crystal for 200 GeV positive pions; (b) DREAM energy deposits for events with a small (grey) and a large (red) C/S value.

VI. Preliminary results for a BGO homogeneous calorimeter used together with DREAM

In this last section we try to estimate the effect of the dual-readout method on BGO on the energy response of a system composed of a BGO homogeneous calorimeter located in front of the DREAM calorimeter. For this we carefully aligned the single BGO crystal to the beam line and we took data with 200 GeV positive pions both with the BGO crystal and the DREAM calorimeter.

We then selected events with a small and a large Cherenkov to scintillation ratio (C/S) measured in the BGO (see figure 7a), and for these two classes of events we histogrammed the energy deposit recorded in the DREAM scintillating fibers. The result is show in figure 7b. An event selection based on C/S allow to clearly distinguish two different contribution to the total energy deposited in DREAM. The separation obtained here is much more evident than what was shown on figure 4b, indicating that with the presented technique one can obtain - in the case of BGO - a better Cherenkov to scintillation separation with respect to what was obtained for $PbWO_4$. We are planning for the future more quantitative measurements with a BGO crystal matrix positioned in front of the DREAM calorimeter.

VII. Conclusion

The work reported in this paper indicates that the separation of Cherenkov and scintillation components in homogeneous materials is possible. The application of the dual-readout method to electromagnetic calorimeters can be used to improve the global (homogeneous and sampling part) calorimeter performance to both electron and hadron showers.

In this work we gave some indication on how to select some homogeneous crystals and how to efficiently separate the Cherenkov and the scintillating components on the basis of their physical characteristics. Preliminary results obtained with a BGO crystal readout through a UV-bandpass filter appear very promising. More quantitative measurements with a full BGO matrix positioned in front of the DREAM calorimeter are foreseen for the 2008 beam test campaign.

Acknowledgment

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References

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