Crystals for dual-readout calorimetry

Gabriella Gaudio[1]

Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, via Bassi 6, 27100 Pavia

E-mail: `gabriella.gaudio@pv.infn.it`

Abstract. Dual-Readout calorimetry was proposed as a technique to eliminate the factors that limit the performance of hadron calorimeters such as electromagnetic fraction fluctuations and invisible energy fluctuations in the shower development. By comparing the signals generated by the Čerenkov and scintillation light components, it is possible to determine the electromagnetic shower fraction on an event-by-event basis. Experimental tests with the Cu-fiber DREAM calorimeter have clearly demonstrated the validity of this principle. Some high-Z scintillating crystals offer the possibility of measuring independently the contributions of the scintillation and Čerenkov lights exploiting the different characteristics of the generated signals. Among these crystals there are BGO and $PbWO_4$. We have tested matrices of these crystals as electromagnetic calorimeters and studied the properties of the Čerenkov and scintillation components of the signals generated by high-energy electrons showering in these detectors. We evaluated the performance of such matrices as a part of the electromagnetic section of a detector for the dual readout technique.

1. Introduction

The Dual-Readout technique is based on the simultaneous measurement, on an event-by-event basis, of Čerenkov and scintillation light components. Čerenkov light is only produced by relativistic particles, dominated by the electromagnetic component of the hadron shower, while scintillation light is a measure of the visible deposited energy. This allow a direct measurement of the electromagnetic fraction (fem) of the hadron shower, thus correcting for one of the most important sources of fluctuations that limits the hadronic calorimetry.

High-Z scintillating crystals are widely used in particle physics experiments since they ensure excellent energy resolution for electromagnetic showers. On the other hand, calorimeters using a crystal electromagnetic compartment usually have a poor hadronic resolution due to fluctuation of the shower starting point in the EM section and to the different response to the em and non-em component of the shower in the two calorimeters. Application of the Dual-Readout Method to an hybrid system may improve the performance of such a calorimeter since measuring the fem on an event-by-event basis allows to correct for such fluctuations and thus to eliminate the main reasons for poor hadronic resolution.

Over the past few years many measurements have been done by the DREAM collaboration on individual crystals to assess the possibility to split the signals in the Č and S components using four different techniques. In this paper the tests performed with crystal calorimeters large enough to contain em showers are described. The two lights components have been separated and the performances of each of these has been studied.

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[1] On behalf of the Dream - RD52 collaboration

Crystals for dual readout calorimetry must allow for a good Čerenkov vs Scintillation separation, a good response uniformity and a high Čerenkov light yield to reduce contributions of photo-electron (p.e.) statistics to the resolution. The aim of the current study is to determine if crystals optimized for dual readout still guarantee a good em resolution. We used two matrices, one made of BGO crystals and one of $PbWO_4$ [1].
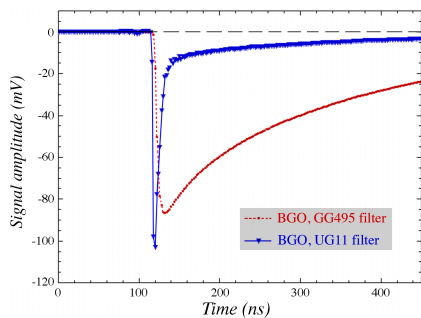

Figure 1. The time structure of typical signals measured in a single BGO crystal. The crystal was equipped with a yellow filter on one side and with a UV filter on the other.
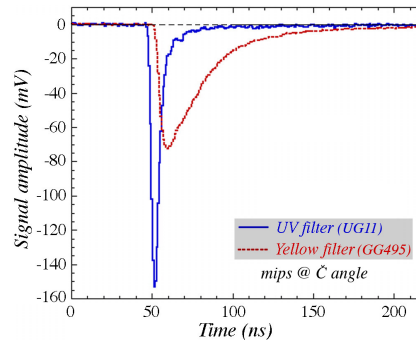

Figure 2. Average time structure of the signals from a single Mo-doped $PbWO_4$ crystal, equipped with a yellow filter on one side and with a UV filter on the other.

2. Experimental setup

In previous studies four techniques were found to allow for separation of the Čerenkov and Scintillation light component, based on the different characteristics of their emission [1]. In the present study we only exploit differences in the optical spectra and time structure.

Čerenkov light is mainly emitted in the UV region and shows a spectral characteristic of the type $\frac{dN_C}{d\lambda} = \frac{k}{\lambda^2}$ while scintillation emission is strongly dependent on the crystal type and it's usually concentrated in a (narrow) wavelength range. Since the crystal we used are quite bright scintillators, the scintillation component needed to be suppressed in order to extract the Čerenkov light by means of an UV filter. A yellow filter is also used to select a pure scintillation signal.

Moreover Čerenkov is emitted instantaneously and the signal duration is usually short, using fast enough PMT . On the contrary, scintillation light emission is characterized by one or several time constant, often showing the presence of long tails (slow components). By using a multi-sample digitizer to record the time structure it is possible to optimize the signal separation by integrating on only a part of the pulse shape. We used the CAEN V1742 digitizer, based on the DRS-IV chip, which allows for GHz range sampling [2]. Examples of the separation of the Čerenkov and Scintillation signals achievable with the two different techniques described are visible in figures 1 and 2, for BGO and $PbWO_4$ respectively.

3. BGO matrix measurements

The BGO matrix consisted of 100 crystals from a projective tower of the L3 experiment. They are 24 cm long and tapered in shape, with end faces of $2.4 \times 2.4 \ cm^2$ and $3.2 \times 3.2 \ cm^2$, respectively. The crystals are arranged as shown in figure 3 and readout by 16 PMTs (Hamamatsu R1355), each collecting light produced by clusters of at least 9 adjacent crystals [3]
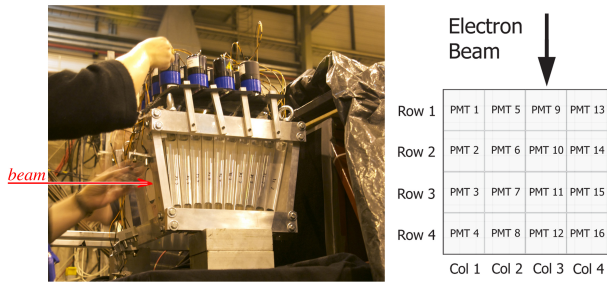
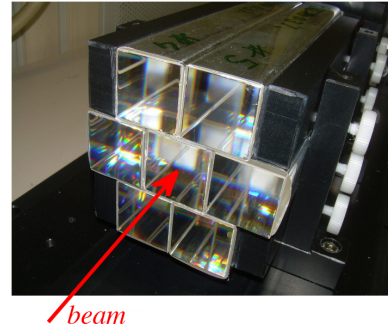**Figure 3.** The BGO matrix and the PMT readout schema.

Figure 4. The $PbWO_4$ crystals positioned in the matrix

Table 1. Properties of the different optical transmission filters that have been used in the studies of the BGO and Mo-doped $PbWO_4$ crystals.

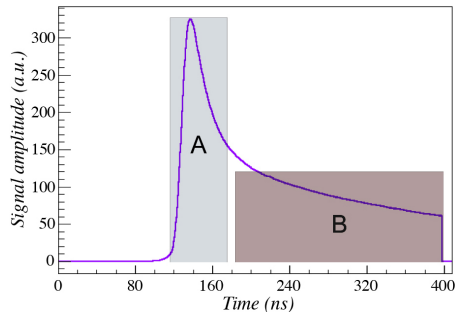| Filter type	Filter name	> 90% transmission for
UG11	"UV"	$\lambda < 400nm$
U330		$\lambda < 410nm$
UG5	"Blue"	$\lambda < 460nm$
GG495	"Yellow"	$\lambda > 495nm$

Figure 5. Average waveform for 100 GeV electrons in the BGO crystal matrix. The data measured in areas A and B were used to decompose the signals into Čerenkov and scintillation components

The BGO crystals are readout on a single side, equipped with a UG11 filter (see table 1) transmitting less than 1% of the scintillation light. This reduction is needed in order to extract the Čerenkov light. The inter-calibration of PMT is done both with LED and with the electron beam steered in each PMT column (see figure 3 right).

The signal obtained event-by-event from the digitizer, is integrated offline over different time windows in order to extract the fast component, the Čerenkov light, (gate A of figure 5) and the slow component, scintillation (gate B). To subtract the residual scintillation component in gate A, the scintillation pulse shape is modeled on pure scintillation pulses (yellow filter signals) and folded to region B of the UV filtered signal

The measurements have been performed with electron beams of 30, 60, 100, 150 GeV. The energy resolution is shown in figure 6 for the Čerenkov and scintillation light separately, and for the sum of the two contributions. For the Čerenkov light the resolution is about $36\%/\sqrt{E}$, mainly due to the low light yield of about 6 p.e./GeV. It also shows a constant term of about 1.5%. The scintillation resolution obtained is of order of $19\%/\sqrt{E}$, caused by the low photo-statistic left after the light filtering. Both signals, on the other hand, show good linearity, within $\pm3\%$,
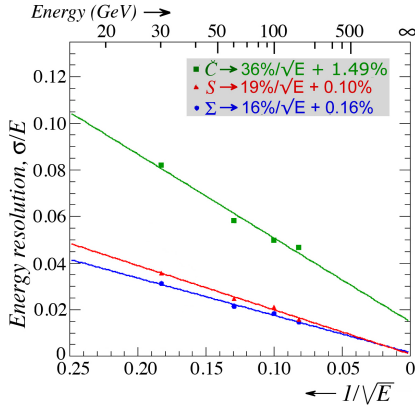
as shown in figure 7.

Figure 6. The energy resolution for electrons in the BGO matrix, as a function of the energy of the showering particles. Results are given for the total charge collected by the PMTs, and for the Čerenkov (C) and scintillation (S) components of the signal.
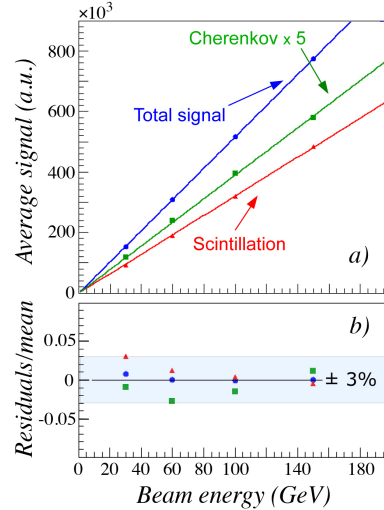

Figure 7. Linearity of the BGO matrix for electron detection. Shown are the average total integrated signal, as well as the Čerenkov and scintillation components of that signal, as a function of energy.

3.1. Comparison BGO and BSO

Other tests were performed to compare of BGO and BSO single crystals in terms of properties for applications in dual-readout calorimetry [4]. Both crystals are 18 cm long and $2.2 \times 2.2\ cm^2$ in cross-section and were tested with a 180 GeV pion beam. Due to the fact that in the spectral range the self-absorption edge is at lower wavelengths for the BSO, the Čerenkov light yield, in terms of p.e. detected per unit of deposited energy, is 2-3 times larger than in BGO. Also the purity of the Č signal obtained with filters achieved a separation power better by a factor of 6 for BSO, while the light attenuation length for Čerenkov light is almost the same in both crystals. Looking at these properties, BSO turns out to be a promising crystal for dual readout even though no further test has been performed at present.

4. $Mo : PbWO_4$ measurement

The $PbWO_4$ matrix is constituted by 7 custom made crystals doped with 0.3% Molybdenum. They were developed to optimize their properties for dual-readout calorimetry [5]. Crystals are $3 \times 3 \times 20\ cm^3$, corresponding to 22.5 X_0 in the longitudinal direction. Each crystal is read out at both ends, with Hamamatsu 8900 and 8900-100 (SBA), for the Scintillation and Čerenkov light, respectively. Calibration has been performed with 30 and 80 GeV electron beam steered in each crystal and by using Geant4 simulation to get the calibration constant: it was found that 77% of energy was deposited in the hit crystal, while 93% of the energy was contained in the entire matrix.

Different filter combinations (table 1) were used during the $PbWO_4$ matrix test, in order to optimize various aspects of the readout. In the first configuration we used a yellow filter upstream and the U330 downstream. This allows for good scintillation resolution of order of ∼1% for 100
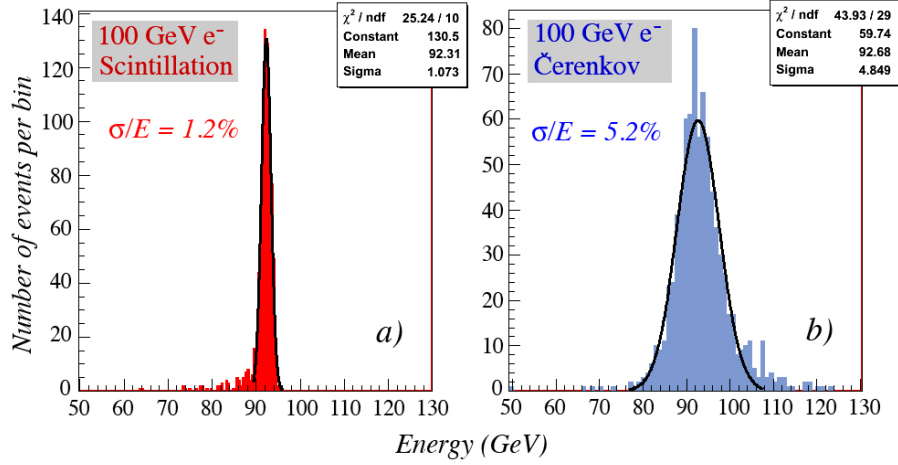
Figure 8. Signal distributions for 100 GeV electrons detected in the $PbWO_4$ crystal matrix, for the scintillation (a) and Čerenkov (b) components of the signals. The scintillation signal was obtained from a GG495 filter mounted at the upstream end while the Čerenkov signal was measured by using the light selected with a U330 filter.
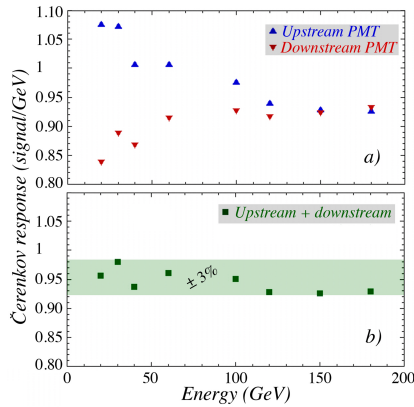

Figure 9. Signal linearity for electrons detected in the Mo-doped $PbWO_4$ crystal matrix for the Čerenkov signals. The matrix was equipped at both end faces with U330 filters and the signals are shown both separately (a) and added together (b).
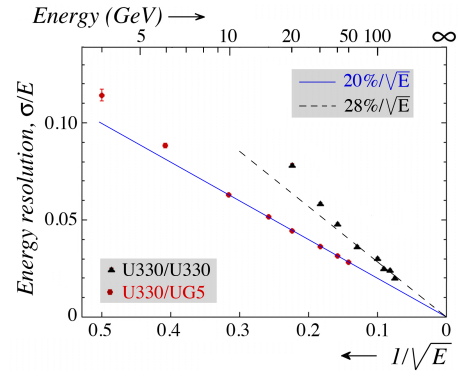

Figure 10. Energy resolution for electrons showering in the $PbWO_4$ crystal matrix, as a function of energy for two different filter configurations (see text for details).

GeV electrons (figure 8a). Unfortunately the small number of photoelectrons and the vicinity to the self absorption edge cause poor resolution (figure 8b) and strong non linearity for the Čerenkov light.

A second configuration uses U330 filters on both sides. This allows to add the signals of the two PMTs on event-by event basis, thus eliminating the effect of light absorption and therefore of the non linearity (figure 9). On the other hand, the scintillation light can only be extracted by the tail of the waveform, with the method shown in figure 5 for the BGO, and the number of photoelectrons turned out to be too low.

A compromise configuration implies the use of an U330 filter on the downstream side, for

detecting Čerenkov light, and of the UG5 filter on the upstream side, to allow for more scintillation light transmission. The linearity for Čerenkov light is restored also in this case, and the energy resolution slightly improves due to the higher number of photoelectron detected (figure 10). The resolution for scintillation light is still quite poor, at least a factor of two worse with respect to the one obtained with the yellow filter (figure 11).
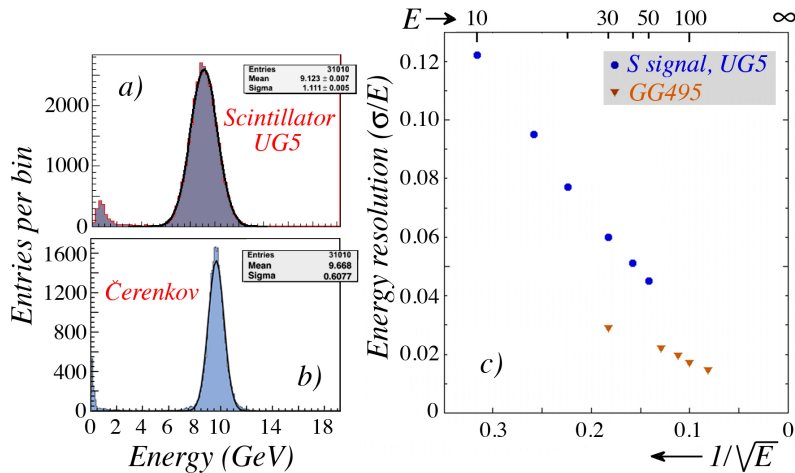

Figure 11. Signal distributions for the scintillation (a) and Čerenkov (b) components of the light generated in the $PbWO_4$ matrix by 10 GeV electron showers and filtered with the U330/UG5 combination. The energy resolution of the scintillation signal is compared with that obtained with the yellow (GG495) filter in diagram c.

5. Conclusions

In order to use crystals in the context of dual readout calorimetry, they have to be read out in a non conventional way, and this leads to results in terms of electromagnetic energy resolution of separated Č and S components that, at present, are far from being optimal and not as good as the ones obtained in standard em calorimetry. In fact, extracting sufficiently pure Č signals from these scintillating crystals implies that a large fraction of the potentially available Č photons needs to be sacrificed (by means of optical filters). Therefore the light that does contribute to the Č signals is strongly attenuated (by UV self absorption).

Our results show that the stochastic fluctuations in the Čerenkov channel are at best $20\%/\sqrt{E}$ in the case of our Mo-doped $PbWO_4$ crystal matrix. Assuming that these fluctuations are completely determined by photoelectron (p.e.) statistics, this would mean that the Č light yield for the electron showers was 25 p.e./ GeV of deposited energy.

Crystals in combination with filters does not seem to offer a benefit in terms of the Č light yield in dual-readout calorimeters. We recently measured a light yield in excess of 50 Č p.e./GeV in our new dual-readout fiber calorimeter. Nonetheless there is room for improvement by optimizing both the crystals and the readout.

References
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