New Results from the DREAM project

Gabriella Gaudio[a]

Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, Pavia, Italy

[a] *On behalf of the DREAM Collaboration*

Abstract

The Dual REAdout Method (DREAM) allows to improve the performance of hadronic calorimeters by measuring on an event-by-event basis the electromagnetic fraction of the hadronic cascade, thus reducing the effect of its fluctuation and obtaining a better resolution and linearity. The method is based on the separation of the scintillation light due to ionization from Čerenkov light produced almost exclusively by relativistic particles, i.e. the electromagnetic component of the hadronic shower. The DREAM method has been applied to both a fiber calorimeter and homogeneous media (crystals). Moreover, with this same technique the neutron fraction can be measured, therefore reducing also the effect of the fluctuations in the invisible energy in sampling calorimeters.

Key words: Calorimetry,

1. Introduction

The performance of hadronic calorimeters are affected by large fluctuations on both the electromagnetic fraction and invisible energy, besides contributions that are also typical of electromagnetic calorimeters. The Dual REAdout Method (DREAM) is based on the separation of the scintillation light due to ionization from Čerenkov light produced almost exclusively by relativistic particles, i.e. the electromagnetic component of the hadronic shower. This allows for an event-by-event measurement of the electromagnetic fraction, resulting in a better resolution and linearity. In fact, the ratio of the two signals can be used to determine the value of $f_{\rm em}$ on an event-by-event basis using the relation

$$\frac{Q}{S} = \frac{f_{\rm em} + 0.21\,(1 - f_{\rm em})}{f_{\rm em} + 0.77\,(1 - f_{\rm em})} \tag{1}$$

where 0.21 and 0.77 represent the h/e ratios for Čerenkov and scintillator fiber structures, respectively, of the DREAM module described in [1] .
The DREAM method has been applied to both a scintillating/quartz fiber calorimeter and homogeneous media. The former has the advantage of a straightforward separation of the two types of light, using two different types of media. The latter usually shows an higher light yield.

2. Crystals for Dual readout technique

Separation of Čerenkov (C) and scintillation (S) light in crystals can be achieved by exploiting differences in their properties:

- time structure: Čerenkov light is prompt, while scintillation is characterized by one or several time constants.
- spectral properties: Čerenkov emission exhibits a λ^{-2} spectrum, while for scintillation the emission spectrum is characteristic of the crystal type, usually it shows some peaks.
- directionality: Čerenkov light is emitted at a characteristic angle $\theta = arccos(1/\beta n)$, while scintillation is isotropic (not exploitable in real detectors but useful for quantitative evaluations).

Both lead tungstate ($PbWO_4$) and BGO crystals have been successfully tested as homogeneous media for dual readout technique. To demonstrate the principle we adopted a readout

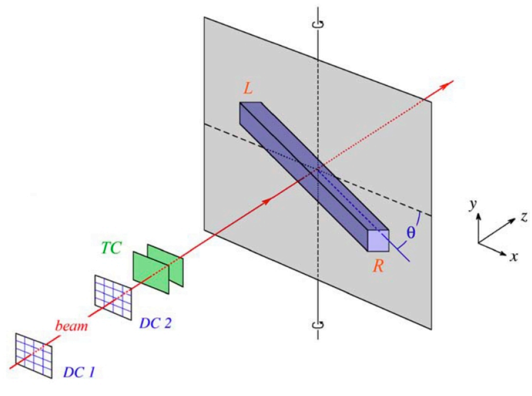

Figure 1: Experimental setup in which the beam tests of the crystals were performed. The angle θ is negative when the crystal is oriented as drawn here..

scheme which consists of two PMTs, one at each side of the crystal, equipped with a short-pass filter for selecting Čerenkov light, and a long-pass filter for scintillation[1]. In order to ex-

[1] Single side readout has also been tested, exploiting the time structure of the signal in order to disentangle the two signal contributions. This is indeed

ploit directionality of the Čerenkov light we performed measurements rotating the crystals at different angles, as shown in Fig. 1.
In our studies we observed that the best possible separation between the two types of light can be achieved when scintillation emission is in a wavelength region far from the bulk of the Čerenkov signal (blue region) and shows a decay time of order of tenths of nanoseconds. Based on work from M. Nikl and collaborators [2] we developed a dedicated crystal with optimal properties for the dual readout method.

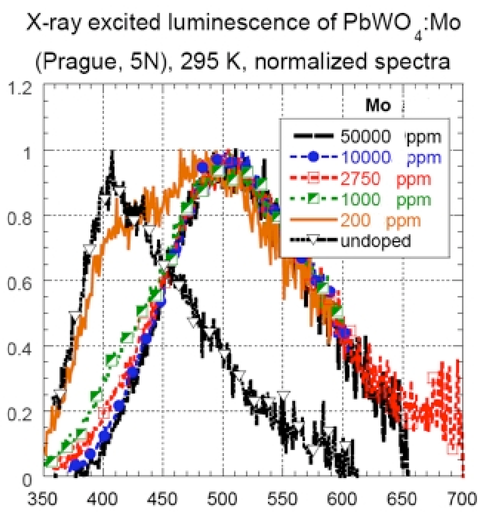

Figure 2: Radioluninescence spectra for undoped and Mo doped $PbWO_4$ crystals.

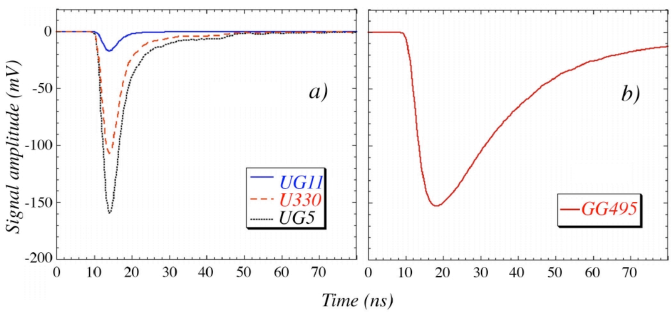

Figure 3: Average time structure of the signals as seen at the two ends of the crystals: (a) three different short-pass filters with different cut-off edges have been chosen to select Čerenkov light; (b) long pass filter used to select scintillation light.

2.1. Molybdenum doping in $PbWO_4$ crystals

Undoped lead tungstate crystals have been tested for the dual readout technique. The achievable separation is not optimal due to the fact that scintillation emission is in the blue region

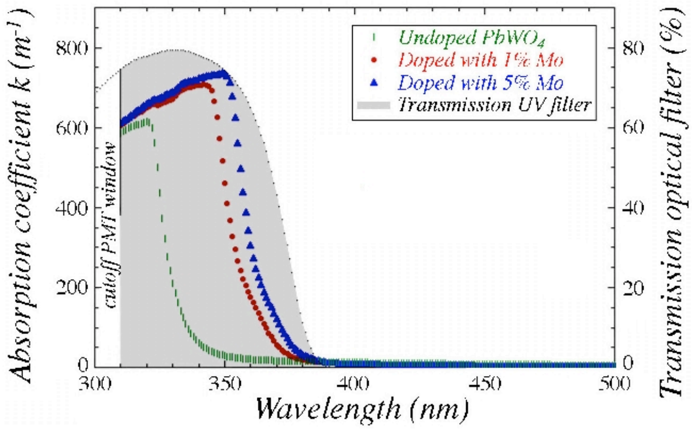

Figure 4: Absorption spectra for undoped and Mo-doped $PbWO_4$ with two different concentration (1% and 5%). The grey area represents the transmission spectrum for the used filter. The allowed wavelength window for Cherenkov light is the grey region to the right of the absorption cut-off.

and quite fast, therefore quite similar to the Čerenkov signal. Both effects can be overcome by doping the lead tungstate with a small quantity of Molybdenum (Mo). The presence of the dopant shifts the emission peak from about 420 nm to about 500 nm (Fig. 2) and increases the scintillation decay time to about 50 ns. These characteristics allow for a better separation of the Čerenkov and scintillation light with the help of dedicated optical filters [3]. In particular a long-pass yellow filter, with a cut-off of 495 nm is used for the scintillation light, while three types of short-pass filters have been used: UG11 with cut-off of 390 nm, U330[2] with cut-off of 400 nm and UG5 with a cut-off of 420 nm. In Fig. 3 time spectra obtained with the different filters are shown[3]. It has been observed that one obtains the better separation using the shortest wavelength filter cut-off. Unfortunately this is obtained at the cost of both a reduction in light yield and shorter attenuation length. In fact, this causes also a shift of the self-absorption cut-off to higher wavelengths and therefore crystals are less transparent to Čerenkov light because the useful window for light collection between self-absorption edge and filter cut-off is narrower. This is shown in Fig. 4 for 1% and 5% Mo concentrations.
Different Mo concentration values cause a change in both the emission spectra and the self-absorption edge position, as seen in Fig. 2 and Fig. 4, respectively. Therefore systematic studies on the Mo concentration (0.1% to 5%) have been carried out [4].
The time structure of the signals, the C/S ratio, the effect of light attenuation and the Čerenkov light yield have been used as figures of merit for the use of the various crystal for Dual Readout Technique. An example of the C/S ratio is shown in Fig. 5.
Preliminary results show that we are able to obtain a Čerenkov light yield as high as 60 p.e./GeV while keeping an attenuation

the baseline RO scheme for BGO.

[2]The UG11, UG5 and GG495 filters were produced by Schott, the U330 filter by Hoya.

[3]PMTs are readout with a 2.5 Gigasample digital oscilloscope which allows for signal shape recording.

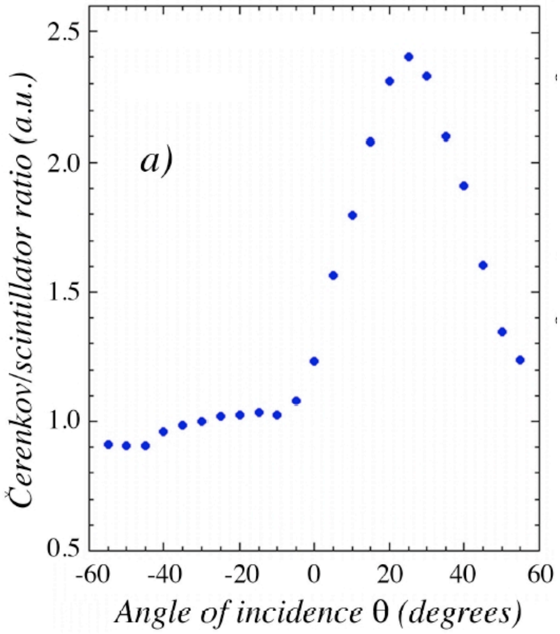

Figure 5: The C/S signal ratio as a function of the angle of incidence of the beam particles for a Mo concentration of 0.1% and a short-pass filter U330.

length of 25 cm and a C/S ratio of order of 2.

3. Combined calorimetry

We have proven that a better hadron calorimeter resolution can be obtained with the dual readout method both in homogenous and fiber detectors. Depending on the physic goal of the experiment, one could be forced to have an electromagnetic resolution at the level of few percent. Since the sampling fluctuations, both due to sampling fraction and sampling frequency, usually dominate the resolution of an electromagnetic sampling calorimeter it is possible to use an hybrid system with a crystal-based electromagnetic section (ECAL) and a fiber hadronic calorimeter(HCAL), both readout with the DREAM technique. We have tested such an hybrid system using the original fiber detector [1] as hadronic calorimeter and a matrix of about 100 BGO crystal as an electromagnetic section [5].
The crucial aspect of the DREAM method is the comparison of the scintillation and Čerenkov signals produced in hadronic shower development. The ratio between these two signals is a measure for the em shower fraction. In the case of the fiber detector in stand-alone mode, there is a simple one-to-one correspondence between this signal ratio and electromagnetic fraction. For the combined BGO+fiber system, such a simple relationship does not exist, since the e/h value of the BGO calorimeters is different from those of the fiber detector, and the energy sharing between these two calorimeters varies from event to event. Due to the small size of the BGO matrix, large hadronic signals in the ECAL section were likely to be caused by energetic π^0s produced in the early stage of the shower development. Therefore, one can expect that hadronic events in

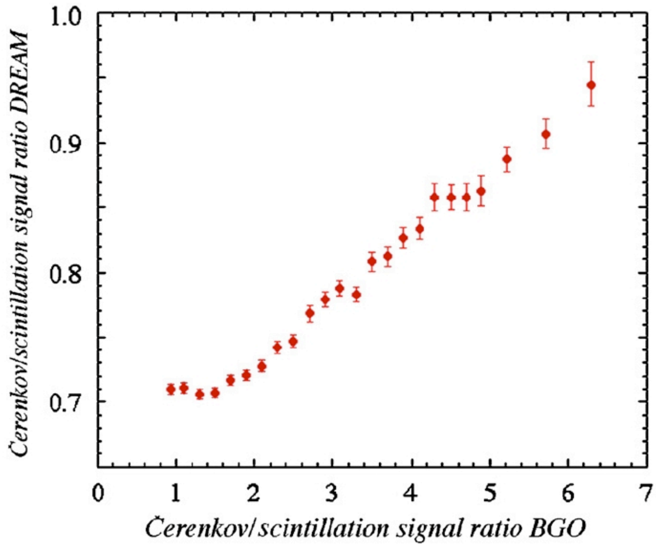

Figure 6: Correlation between the C/S ratio as obtained in the BGO matrix and that obtained in the fiber detector.

which a considerable fraction is deposited in the BGO also exhibit substantial Čerenkov signal in the HCAL. In other words, one should expect the C/S signal ratios in both sections of the calorimeter system are correlated. Fig.6 shows and example of such a correlation. Also in this case, the ratio of the Čerenkov and scintillation signals itself turns out to be a good measure for the em shower content.

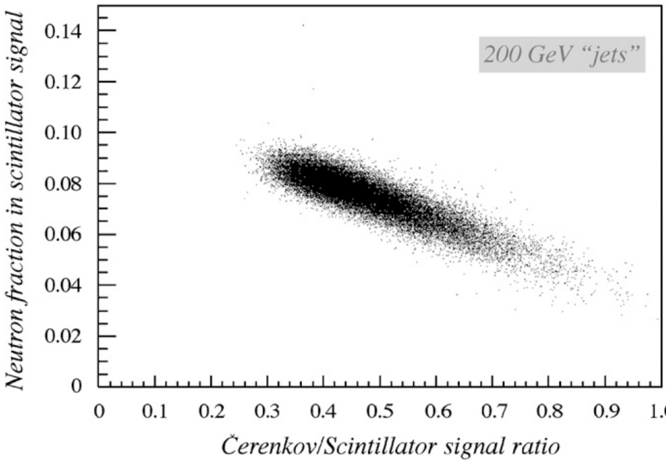

Figure 7: Scatter plots for 200 GeV "jets". For each event, the combination of the total Čerenkov/scintillation signal ratio and the fractional contribution of the neutrons to the total scintillation signal is represented by a dot.

4. Neutron fraction measurement

Once the contribution to the hadronic resolution due to fluctuations in the electromagnetic fraction and other effects, as for example leakage, is reduced, the resolution becomes dominated by nuclear breakup effects. Fluctuations in the fraction of the

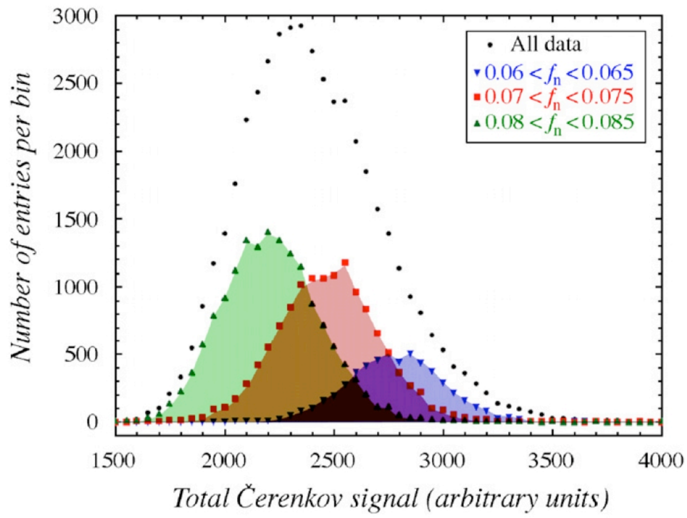

Figure 8: Distribution of the total Čerenkov signal for 200 GeV "jets" and the distributions for three subsets of events selected on the basis of the fractional contribution of neutrons to the scintillator signal

total energy needed to release protons, neutrons and heavier nuclear fragments in the nuclear reactions initiated by the shower particles lead to fluctuations of the visible energy, and thus to fluctuations in the calorimeter response.

It has been demonstrated previously that a measurement of the total kinetic energy carried by neutrons generated in the shower development is a powerful tool for reducing the effects of these fluctuations, especially in high-Z absorber materials where most of the nucleons released in the nuclear reactions are indeed neutrons. It is possible to determine for each event relative contribution of the neutron (f_n) by analyzing the time structure of the signals [6]. In fact, the neutron contribution can be recognized as a tail in the scintillation signal with a characteristic time constant which is correlated to the neutron mean free path in the calorimeter (about 20 ns in the DREAM fiber module) and f_n can be estimated by the relative contribution of this tail. This fraction is anti-correlated with the Čerenkov/scintilation signal ratio and thus with the relative amplitude of the em shower component. This can be clearly understood by the fact that a large C/S means that a large fraction of the shower energy has been transferred to the electromagnetic component and therefore, small energy is available for non-em shower development, and in particular, to nuclear reaction during which neutron would be released, and vice versa. An example of such anti-correlation is shown in Fig. 7. The results shown are for so called 200 GeV "jets" obtained by sending the beam on a target positioned upstream the calorimeter.

To study the merits of this approach event samples with different neutron fractions (f_n) were selected (Fig. 8). The total Čerenkov signal distribution for all the events turns out to be a superposition of many distributions. Each of these distributions for the subsamples has a different mean value, is much more Gaussian than the overall signal distribution and shows a resolution that is substantially narrower than that of the overall signal distribution.

5. Conclusions

The DREAM method consists in the simultaneous measurement of scintillation light due to ionization and Čerenkov light produced almost exclusively by relativistic particles, i.e. the electromagnetic component of the hadronic shower. From this information it is possible to obtain on an event-by-event basis a measurement of the electromagnetic fraction in the hadronic shower, thus reducing the effect on the resolution of its fluctuations. Using a similar technique, it is also possible to reduce effects of the invisible energy fluctuation by measuring the neutron fraction, again on an event-by-event basis.

This technique has been extensively tested on both sampling and homogeneous calorimeters. Preliminary tests on an hybrid system consisting of a crystal em section and a fiber hadronic section also show encouraging results.

References

[1] Akchurin N. et al., Nucl. Instr. and Meth. A537 (2005) 537

[2] Nikl M. et al., Journal of Applied Physics, 91 (2002), 2792

[3] Akchurin N. et al., Nucl. Instr. and Meth. A604 (2009) 512.

[4] Akchurin N. et al., Optimization of crystals for applications in Dual Readout Calorimetry to be submitted to Nucl. Instr. and Meth. A

[5] Akchurin N. et al., Nucl. Instr. and Meth. A598 (2009) 710

[6] Akchurin N. et al., Nucl. Instr. and Meth. A598 (2009) 422