Optimization of Crystals for Applications in Dual-readout Calorimetry

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Abstract. Dual-Readout Calorimetry is a promising new technique for high resolution hadron and jet calorimetry. It is based on simultaneous measurements of the scintillation and Cherenkov light generated in the shower development process. Due to the fact that the Cherenkov light is only produced by the electromagnetic shower component, the relative contribution of this component to the signals can be measured on the event by event basis, resulting in reduction of fluctuations. This leads to an important improvement in the hadronic calorimeter performance. Further improvement on both the electromagnetic and hadronic resolution can be achieved by using homogeneous, dense crystals. This reduces both the sampling fluctuations and the quantum fluctuations. We present a systematic study of lead tungstate crystals doped with a small fraction of molybdenum, varying between 0.1% and 5% and exploring different readout configurations.

1. Introduction

We have performed systematic studies of lead tungstate crystals ($PbWO_4$) doped with a small fraction of Molybdenum (Mo). These crystals were exposed to a beam of 50 GeV electrons and the signals were unraveled into scintillation and Cherenkov contributions, using the time structure of the signals and/or different types of transmission filters. These studies were carried out in view of the possible application of such crystals in dual-readout calorimetry. Key elements for application of the dual readout technique are a clear Cherenkov/Scintillation separation, a good response uniformity and an high light yield, in order to reduce contributions to the resolution due to p.e. statistics. Differences among scintillation and Cherenkov lights which can be exploited in the signal separation are listed in Table 1.

2. The Molybdenum doped Lead Tungstate Crystals

For this systematic study we developed 5 crystals with different Mo concentrations, namely $0.1\%, 0.2\%, 0.3\%, 1\%, 5\%$, among which the last two were already tested in a previous test beam [1]. The effect of Mo on $PbW0_4$ crystals is to shift the scintillation spectrum to longer wavelengths and to achieve a longer decay time. The first effect is illustrated in Figure 1. Unfortunately, Molybdenum has a detrimental effect on crystal transparency at short wavelength, as shown in Figure 2 where UV self-absorption edge clearly depend on doping fraction. The scintillation light is selected using a yellow filter (GG495) which transmits only wavelengths larger than 495 nm, while on Cherenkov side we used three short-pass filters: UG11

Table 1. Properties of Cherenkov and Scintillation lights exploited in signal separation for dual-readout technique.

Properties	Cherenkov	Scintillation
Angular distribution	Light emitted at a characteristic angle by the shower particles that generate it	Light emission is isotropic: excited molecules have no memory of the direction of the incoming particle
Time structure	Instantaneous, short signal duration (few ns)	Characterized by one or several time constants. Long tails are not unusual (slow component)
Optical spectra	λ^{-2} spectrum	Strongly dependent on the crystal, type usually concentrated in a (narrow) wavelength range

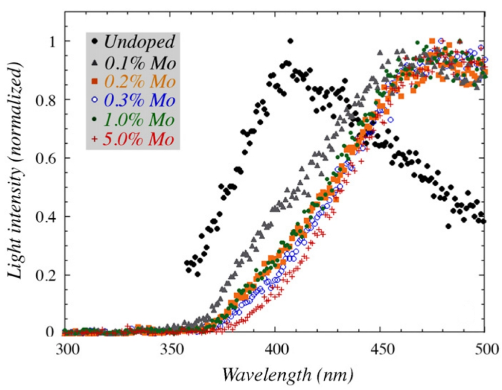

Figure 1. Normalized emission spectra for $PbWO_4$ crystals doped with different fraction of Molybdenum, measured with radioluminescence.

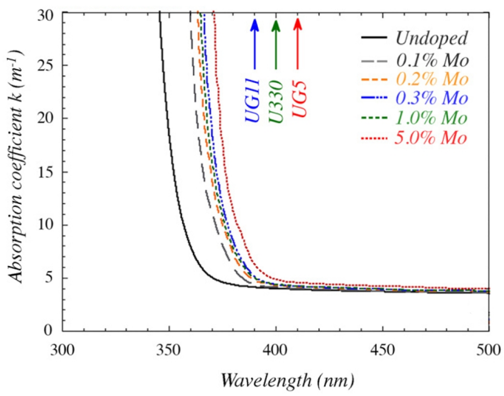

Figure 2. Absorption coefficient as a function of wavelength for $PbWO_4$ crystals doped with different fraction of Molybdenum.

(cut-off $\sim 390\ nm$), U330 ($\sim 400\ nm$) and UG5 ($\sim 420\ nm$)[1] More details on this measurements can be found in [2]

3. Figures of merit

Figures of merit have been individuated in order to compare different configuration of optical filters and Mo dopant concentration. Purity of Cherenkov and scintillation lights can be obtained by measuring C/S ratio over an angular scan performed on the crystals, while response uniformity as function of the position is derived by a measurement of the signal attenuation. Light yield is also measured.

3.1. C/S ratio

In order to evaluate the achievable separation power the ratio of C/S at the Cherenkov angle (30^o in the data taking configuration) and C/S at the anti-Cherenkov angle (-30^o) is measured. In Figure 3 the dependence of this ratios as function of the Mo concentration is shown: the lower

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

the Mo concentration is, the shorter the wavelength at which the scintillation emission starts (see Figure 1), causing more scintillation contamination in the Cherenkov signal and therefore giving a lower C/S ratio. The filter cut-off effect is shown in Figure 4: for lower filter cut-off, the scintillation contamination is smaller and therefore one obtains a larger C/S ratio.
A word of caution should be said about these plots. Each of these crystals was the result of a completely separate production process. Even if the Mo concentration was the only parameter that was deliberately varied, other factors may have deviated as well. Looking at Figure 1 it can be noticed that the red shift of the emission spectrum in the 1% crystal was about the same as for the 0.2% crystal. That means that the scintillation contamination was similar for both crystals, as can be seen in the C/S results and in behavior the other figures of merit.

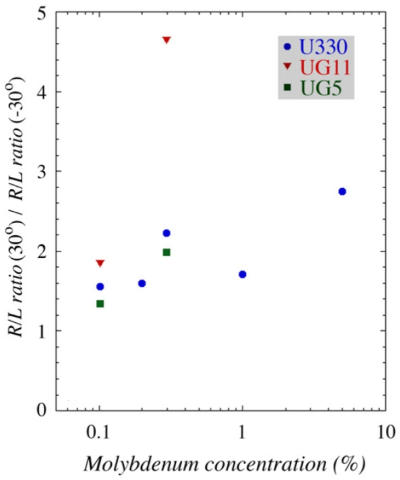

Figure 3. The ratio of the C/S signal ratios measured at 30^o and -30^o as function of the Mo concentration.

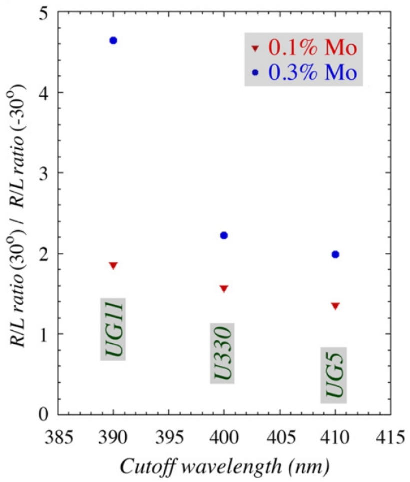

Figure 4. The ratio of the C/S signal ratios measured at 30^o and -30^o for the different filters used and two Mo concentration.

3.2. Light attenuation

As a consequence of the small effective bandwidth between the self-absorption edge and the filter cut-off (Figure 2), the Cherenkov signal is strongly attenuated. We measured the relative change in the Cherenkov signal over a distance of 10 cm of crystal by means of a longitudinal scan. We found that for smaller Mo concentration, the self-absorption edge is more blue-shifted (see Figure 2), and therefore the effective bandwidth is larger reducing in turn the effect on light attenuation (Figure 5). In Figure 6 the filter cut-off effect is shown: for cut-off at shorter wavelength, as seen, the Cherenkov signal effective bandwidth is narrower, and consequently the light attenuation effect is larger.

3.3. Cherenkov light yield

The calibration for the light yield measurement has been carried on using the scintillation signal as a measurement of the deposited energy and assuming from Monte Carlo that the average deposited energy is 0.578 GeV in the experimental configuration. The number of Cherenkov photoelectrons is determined by the fractional width of the corresponding Cherenkov signal distribution σ_{rms}/C_{mean}. Results for light yield are reported in Table 2 for different filter and Mo concentration configurations. It can be noticed that the smaller is the Mo concentration, the lower the self-absorption edge (see Figure 2). This allows for a larger effective bandwidth

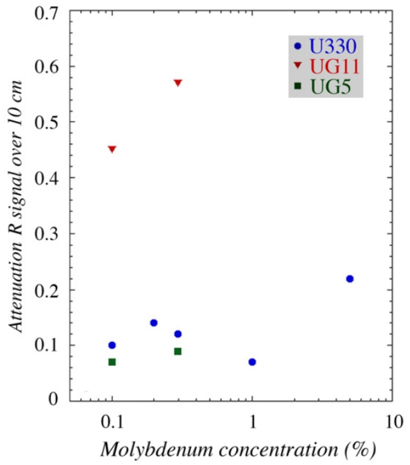

Figure 5. Relative change in the Cherenkov signal over a distance of 10 cm as a function of the Mo concentration in the $PbWO_4$ crystals.

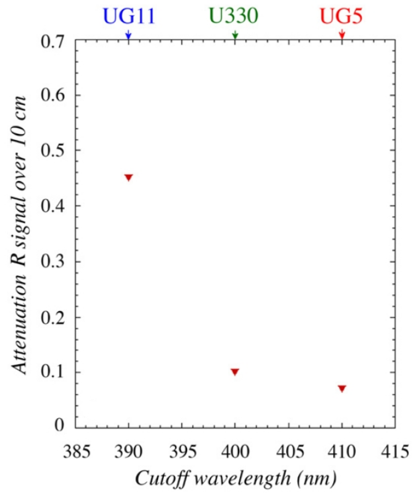

Figure 6. Relative change in the Cherenkov signal over a distance of 10 cm as a function of the optical filter cutoff in the $PbWO_4$ crystals.

for the Cherenkov signal and therefore a larger light yield. From the point of view of the filter cut-off effect, the shorter it is, the smaller the Cherenkov signal effective bandwidth is and, in turn, the smaller the light yield.

Table 2. Cherenkov Light Yield measured for $PbWO_4$ crystals doped with different fractions of Mo. The results are given in p.e./GeV and measured with 50 GeV electron traversing the crystal at an angle of 30^o.

Mo concentration	UG11	U330	UG5
0.1	5	62	
0.2		57	
0.3	6	55	65
1		58	
5		38	

4. Conclusions

We performed a systematic study on $PbWO_4$ crystals doped with small amounts of Molybdenum and using different optical filters. This study was carried out to investigate if this type of crystals is suitable for dual readout technique. An optimal configuration with a dopant concentration of 0.3% and the use of U330 filter shows a sufficiently high light yield (55 p.e./GeV), a reasonable low attenuation ($< 10\%/10\ cm$) while keeping a good Cherenkov to scintillation separation (2.4). A matrix of 7 crystals in this configuration will be tested in 2010 in a test beam.

References

[1] N. Akchurin et al, NIM A604 (2009)
[2] N. Akchurin et al, NIM A621 (2010)