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$PbWO_4$ crystals for the CMS electro-magnetic calorimeter

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In this paper results obtained by the CMS collaboration in the study of the properties of $PbWO_4$ crystals chosen to construct the electro-magnetic calorimeter for the CMS experiment at LHC are reported. The main activities carried out by the collaboration during 1995/1996 were devoted to the definition of the properties of the crystals needed to fully characterise them for the final calorimeter assembly.

1. INTRODUCTION

The CMS experiment [1] design was optimised for the measurement of muons, electrons and photons to have the best performances for the detection of new particles. In the technical report the collaboration stated that the CMS detector should have, besides other characteristics:

1. *a very good and redundant muon system;*
2. *the best possible electro-magnetic calorimeter consistent with 1;*

The reason for that stays in the fact that the Higgs particle (standard and non-standard) decay into muons, electrons and photons in a sizeable fraction of the events and these channels have the cleanest signature. In particular, the most promising channel for the detection of a Higgs boson in the intermediate mass range (90-130 GeV), is $H \rightarrow \gamma\gamma$. In this mass region the natural width of the Higgs is very small and the signal to noise ratio will be entirely dominated by the experimental resolution in the invariant mass reconstruction.

These considerations lead to the design of a high resolution electro-magnetic calorimeter, finely segmented to lower the pile-up noise contribution and to increase the π^0 rejection and the position resolution, compact to reduce costs and fast enough to cope with the repetition rate of the beam crossings at LHC (25 ns).

It was decided to realize such a detector as an homogeneous e.m. calorimeter made of $PbWO_4$ (PWO) crystals. In table 1 some of the characteristics of few scintillating crystals are reported. From the table it can be seen that PWO is the crystal with the shortest radiation length allowing the construction of the smallest detector with respect to the others. Moreover it is very fast, most of the light being emitted in, at most, tens of ns. On the contrary the light yield is modest compared to other crystals, but this difficulty can be overcome by using suitable photo-detectors such as APDs [2].

This paper is organised as follows: in section 2 we will give an overview of the results obtained in growing and cutting technology; in section 3 the scintillation properties are summarised; in section 4 the light collection problem is described, while in section 5 we will report on recent results about the radiation damage.

2. GROWING AND CUTTING

PWO crystals can be grown by the Czochralski method as well as the Bridgman method. They are grown starting from a mechanically mixed compound of PbO and WO_3 in stechiometric ratio that melt at 1163 °C. Continuous interaction between high energy physicists and producers has lead to some optimisation in the techniques. For example it was shown that PWO samples grown in oxidising atmosphere tend to become yellow, while samples grown in neutral atmosphere are almost colourless. Also the scintillation properties are affected by the growing technique: in

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Table 1
Properties of some scintillating crystals. The superscripts f and s stay for *fast* and *slow* component respectively[3][4]

	NaI(Tl)	BGO	CeF_3	BaF_2	PWO
ρ (g cm^{-}2)	3.67	7.13	6.16	4.89	8.18
X_o (cm)	2.57	1.12	1.68	2.05	0.89
R_M (cm)	4.5	2.4	2.6	3.4	2.2
λ_{int} (cm)	41.4	22.0	25.9	29.9	22.4
refractive index	1.85	2.20	1.68	1.56	2.29
Light Yield (a.u.)	1	0.15	0.10	0.05^f	0.01
				0.20^s	
decay time (ns)	250	300	10^f	0.7^f	5^f
			30^s	620^s	15^s
peak emission (nm)	410	480	310^f	220^f	440^f
			340^s	310^s	480^s

samples grown by Czochralski method, because of the lower evaporation temperature of the WO_3, crystals tend to present more defects far from the seed side. These defects lead to a non-uniform light yield. To fight against this non-uniformity non-stechiometric WO_3 is added to the melt to compensate for the evaporation. As will be seen in following sections, also the purity of the raw material can influence much the properties of the scintillator, so that care must be taken in the preparation of the initial compound. It was found that post-growing annealing can be useful to remove non-stechiometric oxygen from the crystal preventing the appearance of unwanted absorption bands [5].

Once grown crystals must be cut in a tapered shape, whose dimensions are about $1.8\times2.1\times23$ cm^3. Such crystals must fit into a mechanical structure composed of several alveoli very precisely in order to minimise the dead space between crystals and to avoid adjacent crystals to push each other. With this respect it has to be noted that the required tolerance is very strong (+0/-100 μm) and that since last year, producers have started to deliver much better cut crystals. The RMS of the distribution of the measured dimensions minus the nominal ones was 320 μm in 1995, while it is 40 μm in 1996.

3. SCINTILLATION PROPERTIES

The studies carried on PWO crystals [10] about the scintillation properties have the aim of giving a description of the basic mechanisms of the light emission and help to produce better crystals from the point of view of the light yield and decay time.

For what concern the scintillation kinetics [6] measurements have been taken using photoluminescence and radio-luminescence spectra. All the measurements show that PWO scintillation light has several components. Of them the first is very fast, the decay time being of the order of 1-5 ns. A second component has been found with a decay time of the order of 10 to few tens of ns. Other slower components exists in several samples. The uncertainties in the numbers given above is due to the fact that the decay times vary from sample to sample, as well as the relative weight of the components. Usually the decay curves are parametrised using a sum of three exponentials and an average decay time is defined as the weighted sum of this three components (see fig. 1).

Using time resolved spectra and filters it is possible to separate the components according to their wavelength. It was shown [7] that all the tungstates have a very fast (less than 10 ns) blue component peaked around 410-420 nm. This component is associated to regular WO_4 centres being present in all the investigated samples.

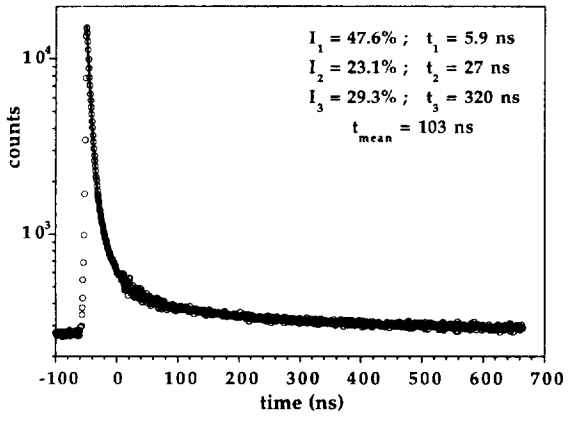

Figure 1. an example of a PWO decay spectrum, fitted using three exponential. The mean decay time is given.

Other components are ascribed to defects in the crystals varying from sample to sample according to growing conditions. The most important of them is a relatively fast (of the order of few tens of ns) green component (480-520 nm) ascribed to the recombination of free carriers. A further slower component was often found (in the first samples this component could have a decay time also of the order of few ms): this component is ascribed to traps created in the crystals by some impurities that slower the free carrier recombination leading to large, even non-exponential tails in the decay.

At the beginning of the production the priority was the increase of the light yield, being very poor in first received samples. This was in fact obtained but at the price of an increase of the mean decay time as can be seen in fig. 2. During 1995 R&D the slow component mechanism was fully understood [8] and the role of impurities (especially of Mo) was found [9]. After the publication of the cited papers producers take a special attention in using new purified material. In table 2 it is shown how the raw material was purified by few elements, in particular from Mo between 1995 and 1996. It was observed (see fig. 2) that the mean decay time of new crystals is much less using purified material, showing that impurities may cause the formation of traps that are in fact revealed and measured using TSL measurements [10].

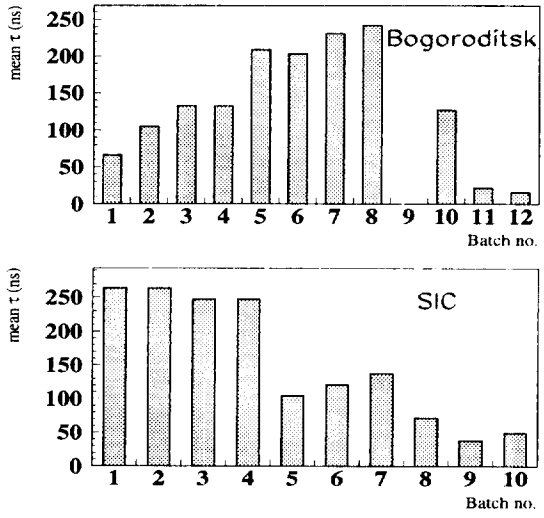

Figure 2. The evolution of the mean decay time with the delivery date for crystals produced at Bogoroditsk and at SIC

The light yield (LY) of PWO crystals is quite poor, so the measurement has to be performed very carefully. In general, it is measured locating the photo-electric peak of radioactive sources and evaluating its width. Due to the low light yield the resolution is such that the Compton edge is merged into the photo-peak, in such a way that the peak position is somewhat shifted. To take into account the Compton background in the evaluation of the peak position a precise technique was developed [11], modelling the spectrum as a Fermi-Dirac like function for the Compton part and a Poissonian for the photo-electric peak. The average light yield at 18°C for long PWO crystals is of the order of 100 photons/MeV, corresponding to about 10-15 photo-

electrons/MeV measured with a standard PMT. In fig. 3 it is shown that, despite the decrease of the green slow component described above, the average light yield is the same for 1995 and 1996 crystals. Moreover in the 1996 distribution there is a tail on the high LY side that corresponds to the newer crystals, showing that some progress were made in increasing the light yield due to a better transparency of the samples.

Optically, crystals are characterised measuring their transmittance both longitudinally and transversally at several distances from the seed size to detect non-uniformity.

In general the optical transmission of lead tungstate crystals has the shape shown in fig. 4, with a strong absorption band located near 320-350 nm, but the slope of the rise after that band vary from crystal to crystal. A sizeable fraction of the crystals show a very sharp step around 350 nm revealing the absence of the absorption band. In the first samples it was observed a correlation between the shape of the transmission curve with the radiation induced absorption coefficient, but this fact was not confirmed later. The different shapes of the transmission curves are not still well understood.

The longitudinal transmission is used to measure the absorption length of the crystal at various wavelength. This parameter is useful in understanding and predicting the light collection properties of the crystal. Because of the birefringence of the crystal the measurement of the longitudinal transmission should be taken with enough care to avoid the loss of the part of the light that goes through the extraordinary ray.

Table 2
Raw material improvement for Bogoroditsk crystals

Element	Impurity Level (ppm) 1995	1996
Na	7.34	3.15
Al	4.98	1.51
Si	2.39	1.19
Ca	3.48	0.87
Fe	2.49	1.40
Mo	160	18.6

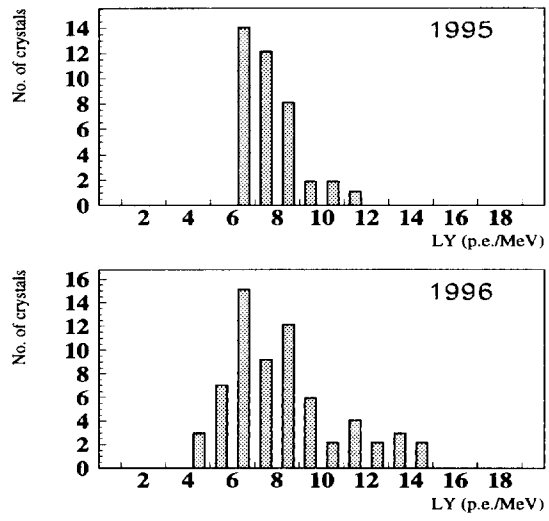

Figure 3. The evolution of the light yield with the delivery date

4. LIGHT COLLECTION

The uniformity in the light collection is a very important parameter for crystals to be used for e.m. calorimetry: a non uniform light collection may cause two effects:

- a non-linearity in the energy measurement: the signal measured by the photo-detector is given by the convolution of the light emission density $S(x)$ (here x defines the coordinate along the crystal axis) and the light collection efficiency $L(x)$

$$V = C \int_0^{l_0} S(x)L(x)$$

If $L(x)$ is not a constant the signal is not linear with the released energy;

- a degradation of the resolution: if the light collection efficiency is not nearly constant

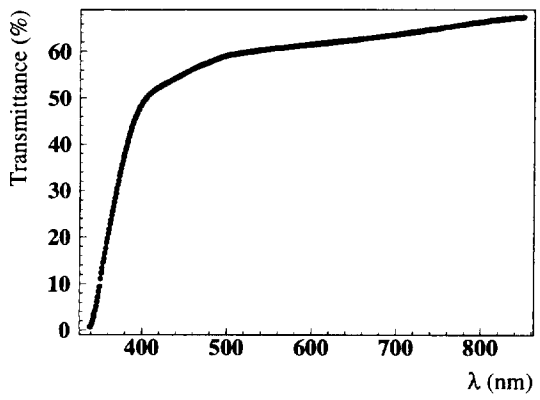

Figure 4. a $PbWO_4$ typical transmission curve

the shower maximum fluctuations will be amplified due to the different weights applied to the light at different x positions.

The light collection efficiency is influenced by the refractive index, the crystal geometry and the absorption length. The extraction of the light from the crystal is difficult, the refractive index being quite high [4]. On the other way it is easier to guide the light toward one end of the crystal. Due to the tapered geometry of the detector the light produced far from the photo-detector is collected more efficiently than the one produced near it because of the focusing effect induced by the tapered walls of the crystal that makes the light produced far from the photo-detector incident with smaller angle on the photo-detector. This effect may be balanced by the absorption of the light inside the crystal that produces the opposite effect.

In order to optimise the light collection several wrappings and coatings are being examined such as tyvek, teflon, millipore, aluminized mylar or paints. Another way to optimise the light collection, as can be seen in fig. 5, is trying to tune the mean absorption length of the crystal to a value such that the response is flat all along the crystal.

Since, as will be explained in the next section, the radiation damage affects mainly the transmission of the light, it is important that a change in the absorption length does not induce a big change in the non-uniformity to avoid loosing resolution. In this case crystals must be selected such that they have an absorption length greater than about 25-30 cm; in this way even a relatively big change in absorption length does not result in a dramatic change of the non-uniformity. No final decision has been taken yet in this field.

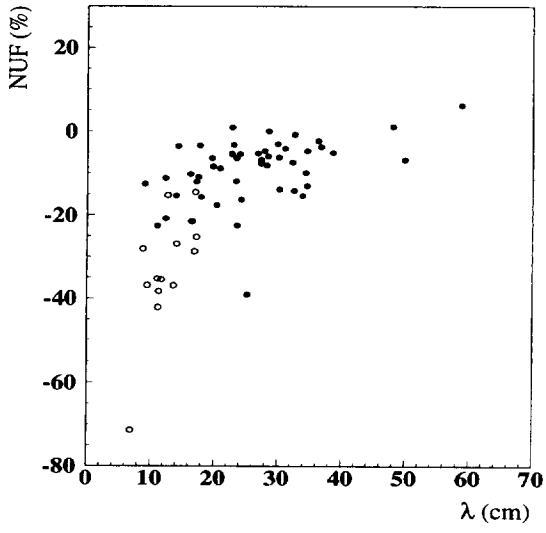

Figure 5. The non-uniformity of several 1995 crystals as measured at PSI (empty dots) and at CERN (black dots) vs the absorption length of the crystal. Here the non-uniformity (NUF) is defined as the ratio $(LY_{front} - LY_{rear})/\bar{LY}$, where LY_{front} is the light yield measured far from the photo-detector and LY_{rear} the one measured near the photo-detector. $\bar{LY}$ is the average light yield

5. RADIATION HARDNESS

The radiation hardness of PWO crystals is investigated [10] damaging samples with both photons and neutrons up to the maximum doses foreseen for 10 years working of LHC [12]. To characterise the damage usually the radiation induced absorption coefficient μ is given:

$$\mu = -\frac{1}{d} ln \frac{T}{T_0}$$

together with the initial transmission curve. It was found that doping PWO crystals with a small amount of Nb (30-50 ppm) is a way to increase the hardness of the crystals.

The absolute value of the radiation induced damage varies from crystal to crystal and R&D is now focused to find correlations to understand what makes some crystals harder than others.

One common feature of the photon induced damage is that it saturates quickly in the first 10 Gy or so. This indicates that radiation does not create new defects in the crystal, but simply fills traps that acts as colour centres. It was also observed that the light yield has an exponential correlation with the radiation induced absorption coefficient, indicating that the damage does not affect the scintillating centres, but only the light transmission allowing the monitoring of the light response by mean of the measurement of their transparency.

For what concerns neutron irradiation it was proved on few samples that the transmission characteristics of the crystals does not change after irradiation up to a fluence of the order of 10^{14} n/cm^2. Once irradiated crystals are more fragile and care should be taken in manipulating it.

A coordinated R&D effort is under way to characterise crystals from the point of view of the radiation damage in order to have a full description of the physical mechanism of the damage itself from which one can start a growing program to improve the quality of the crystals with respect to this aspect.

6. CONCLUSIONS

PWO crystals were chosen for the construction of the CMS electro-magnetic calorimeter. Since then a strong R&D effort was carried on by the institutions responsible for the sub-detector. This large program lead to the optimisation of the growing and cutting techniques and to a better understanding of the basic mechanisms responsible for the light yield of the crystals, providing some hints to make better crystals from the point of view of both the light yield and the decay kinetics.

Experiments are currently on the way to fully understand the radiation induced damage. Some interesting features were found such as the saturation of the damage at low doses and the fact that apparently the damage affects mainly the self absorption of the light rather than the scintillation mechanisms.

Given the results cited above the CMS collaboration is confident to be able to fully characterise the crystals before the end of 1997 for the preproduction phase of the calorimeter.

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