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Overview of PbWO_4 Calorimeter in CMS

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Abstract

The status is given of the Lead Tungstate (PbWO_4) electromagnetic crystal calorimeter for the CMS detector at LHC. This includes the progress about the engineering design of the calorimeter and the readout system, latest results on PbWO_4 crystals and photodetector development, with particular attention to radiation hardness issues, and results from test measurements in particle beams.

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1 INTRODUCTION

The CMS collaboration is developing, for its detector, a high-precision electromagnetic calorimeter (ECAL). Its conception is based on the need to optimize the discovery potential of a light Higgs, with a mass $m_H < 150$ GeV, decaying into two photons. Since the natural width of the Higgs there is expected to be very narrow, and the background from QCD jets huge, the detector resolution is the crucial factor for this kind of signature, which is the only promising one to explore the low mass range in the search for a Standard Model Higgs particle.

2 PbWO₄ calorimeter design

Beyond the benefit of a homogeneous calorimeter, Lead Tungstate has been chosen for several reasons. It has a fast scintillation emission, with a light decay time which matches the LHC bunch crossing time of 25 ns. It has small radiation length ($X_0 = 0.89$ cm) and Molière radius ($R_M = 2.2$ cm), so that a very compact and highly granular calorimeter can be built [1]. However, its light output has a temperature dependence of 2%/°C, which puts some constraints on the detector construction.

The ECAL barrel electromagnetic calorimeter is designed to have an inner radius of 1.29 m and a granularity $\Delta\eta \times \Delta\varphi = 0.0175 \times 0.0175$ using 23 cm ($26 X_0$) long crystals with a front face of $\sim 22 \times 22$ mm² for a total crystal volume of 8.14 m³. Avalanche Photodiodes shall be used as photodetectors. The mechanical design has to take into account several constraints, given by the fragility of the crystals, the need for temperature regulation of crystals and photodetectors, the need for hermeticity and its large dimensions. The design is based on modularity and on the use of high-strength, low-Z materials, where alveolar submodules of 2×5 fiberglass cells containing individual crystals are the smallest subunits. These submodules will carry a reflective inner coating, yielding intercrystal gaps of < 500 μ m. Fifty respectively 40 such submodules (depending on η) are foreseen to be assembled into baskets made out of Carbon-fibre composite, which will take the cantilever of the submodules. Supermodules consisting of 4 baskets held by a U-shaped spine at the outer ECAL radius shall be used for calibration in the test beam and installation. Hermeticity has been optimized by tilting the crystal axis by 3^0 with respect to the direction pointing towards the centre of the detector. The barrel ECAL covers the pseudorapidity region $|\eta| < 1.48$.

The ECAL end-cap calorimeter is designed along a similar scheme, however using identical “supercrystals” containing 6×6 identical crystals, 22 cm long (owing to the presence of a $3 X_0$ thick preshower detector in front) and with $24.7 \times 24.7 \text{ mm}^2$ front face dimensions. The front face of the calorimeter shall be at $\sim 3170 \text{ mm}$ distance from the detector centre along the beam axis, and the crystals will be oriented towards a point located 1300 mm beyond the detector centre for hermeticity. An alveolar fiber-

Figure 1: Longitudinal section of the electromagnetic calorimeter (one quadrant).

glass support structure is foreseen here as well, with the supermodules cantilevered off the front side of “Dee”-shaped, 5 cm thick Aluminium support plates. All readout electronics, from the preamplifier to the fiberoptics readout, is to be sited on the rear of the support plate. The endcap ECAL covers the pseudorapidity region $1.48 < |\eta| < 3.0$.

3 Crystal development

(a) Relative light output loss versus dose for 5 cm long chinese crystal samples irradiated along the side at doserates of 0.15 - 0.25 Gy/h, as measured with a Photomultiplier.

(b) Relative light output loss versus dose for crystal 147-1 (5 cm long) from China, under side irradiation at 4 Gy/h.

Figure 2: Progress on radiation hardness for chinese crystals in 1997.

The development of PbWO_4 crystals with characteristics suitable for use in the CMS ECAL has been concentrating, up to the beginning of 1996, with the improvement of light output and of the mechanical processing. A light yield of > 10 photoelectrons (p.e.)/MeV measured on a XP2262B photomultiplier (PMT) covering the whole back face of the crystal wrapped with Tyvek is required. The measured

Figure 3: Progress on radiation hardness for russian crystals in 1997: relative light output loss versus dose for full size russian crystals measured as the total photocurrent on a hybrid PMT during front irradiation with ^{60}Co at 0.15 Gy/h.

distribution of values in a July 1997 batch of 20 crystals was 10.8 p.e./MeV with $\sigma = 1.3$ p.e./MeV. The measured ratio of light emitted within a 100 ns gate to the light emitted over 1 μ s is for all those crystals, as required, above 90%. Their attenuation length as well is, as requested, longer than 1 m and the mechanical tolerances in the cut crystals dimensions are within the 200 μ m tolerances for more than 95% of the crystals.

The remaining, most critical issue addressed in 1997 is the radiation hardness of crystals. The environment for the CMS ECAL is particularly hostile in this respect. At the highest luminosity of 10^{34} cm⁻²s⁻¹ one expects at the electromagnetic shower maximum dose rates around 0.25 Gy/h in the ECAL barrel, values around 0.30 Gy/h at the barrel-endcap interface and 15 Gy/h at $\eta = 3$. The hadron flux in the calorimeter is almost entirely due to neutrons, and it is expected to reach 2×10^{13} n/cm² in the ECAL barrel for an integrated luminosity of 5×10^5 pb⁻¹ (equivalent to 10 years of running at LHC). However, no damage by neutron irradiation has been seen so far [2], while a sample dependent effect is observed with photon irradiation. It has been shown that the scintillation mechanisms are not damaged, nor is the scintillation emission spectrum changed [3]. The degradation of light output is namely due to radiation-induced absorption, i.e. the formation of colour centres, which reduce the crystal transparency. A believed cause for the formation of colour centres is the presence of Oxygen vacancies. It will be thus possible to monitor the loss in transmission due to irradiation using a light injection system in the calorimeter, and to apply corrections for it.

To compensate for such defects, two different approaches are pursued by the crystal growers. One, for chinese crystal produced via Bridgman method, is a systematically optimized post-growth annealing process. In a first round of developments, such a treatment at temperatures close to the melting point of PbWO₄ in different gaseous atmospheres has been applied to crystals cut in pairs from the same “father” crystal; oxygen-annealed crystals appear considerably more radiation-hard than air-annealed crystals, as can be seen in the comparison between crystals 115-1 and 115-2 of Fig. 2(a), both cut from the same ingot. Further, the best oxygen-annealing cycle has been determined from the highest radiation resistant sample out of two obtained from the same ingot. The reproducibility of such crystals was demonstrated through the delivery of several oxygen-annealed 50 mm long samples, whose behavior under irradiation also appears in Fig. 2(a). Finally, some samples were tested using a radiation dose corresponding to the levels expected at large η in the ECAL end-caps, or, respectively, to the integrated dose after one year of high luminosity running at LHC in the barrel. From the example shown in Fig. 2(b) it can be seen that excellent radiation resistance can be achieved even for such high levels of radiation. For russian crystals grown via the Czochralski method, the crystal quality was optimized using specific dopants, either pentavalent on the tungsten site (using niobium) or trivalent on the lead side (using lanthanum, yttrium or lutetium). A successful compensation of defects was obtained, in that these crystals show an improved transparency, as well as a considerable improvement of radiation hardness, whose progress can be appreciated in Fig. 3.

4 Photodetectors

For the detection of the PbWO₄ scintillation light in the ECAL barrel, Silicon Avalanche Photodiodes (APDs) have been chosen, since they are insensitive to magnetic fields, allowing thus operation in the 4 Tesla CMS solenoidal field, and since they also have some internal gain, as needed with the modest light yield produced by the crystals. Additionally, their quantum efficiency matches well the PbWO₄ emission spectrum. However, several APD parameters had to be optimized, and this has been the object of extensive R&D efforts pursued by manufacturers like EG&G and Hamamatsu, in collaboration with several institutions (U. of Minnesota, PSI, ETH Zürich, RWTH Aachen, RAL, Saclay, U. of Rome I and INFN). The crucial parameters there are the APD capacitance (C), the so-called Excess Noise Factor (F) which quantifies the fluctuations in the multiplication process, the gain (M) stability with respect to temperature and voltage, and the response to ionizing radiation hitting the diode (expressed as an effective thickness d_{eff}). A summary of the achieved performance can be found in Table 1. Concerning

New prototypes (M=50) $T \simeq 20^0\text{C}$										
APD	passivation layer	C(pF)	V_b (V)	I_D (nA)	F	ε_Q (480 nm)	d_{eff} (μm)	$\frac{1}{M} \frac{dM}{dV}$ (%/V)	$\frac{1}{M} \frac{dM}{dT}$ (%/ ^0C)	Area (cm^2)
Ham. (end 97)	Si_3N_4	90	$350 \div 400$	2-3	2	85%	4-5	4	-2.5	0.2
EG&G (mid 96)	Si_3N_4	30	300	30-50	2.2	80%	7-10	1	-3	0.25
CMS requests	Si_3N_4	< 100	< 500	few nA	2	big	small	< 2	< -2	> 0.5

Table 1: Characteristics of Avalanche Photodiodes

the resistance to radiation, it is now established that the APD behaviour corresponds to that of Silicon. The bulk current (I_B) is observed to increase linearly with neutron flux (Fig. 4(a)). For a flux of e.g. $2 \times 10^{13} \text{ n/cm}^2$ (as expected after 10 years of running at LHC), $I_B \simeq 200 \text{ nA}$, which for $M=50$ translates to a dark current $I_D = I_B \times M \simeq 1000 \text{ nA}$. However, dark current (I_D) measurements after irradiation show that it recovers. A measurement [4] over one year has allowed to establish that a fraction of $(35 \pm 15)\%$ recovers with a time constant of 1.3 days, $(25 \pm 5)\%$ with a time constant of (6.7 ± 1.5) days, $(17 \pm 1)\%$ with a time constant of (68 ± 10) days leaving only $(23 \pm 1)\%$ of it which do not recover. After a long-term exposure to radiation, the dominant contribution from APDs to the electronic noise is given by [5]:

(a) APD bulk current 2 days after irradiation, as a function of neutron flux.

(b) APD dark current recovery at 18^0 after irradiation with $1.4 \times 10^{12} \text{ neutrons/cm}^2$.

Figure 4: APD behaviour after neutron irradiation (From Ref. [4]).

$$\sigma(\text{MeV}) = \sqrt{k \cdot I_B \cdot F \cdot \tau} \frac{1}{N_{p.e.}} \times 3$$

where, conservatively, $k = 11.5 \text{ nA}^{-1} \text{ ns}^{-1}$, $F=2.2$, $\tau = 37$ and $N_{p.e.} = 6$ photoelectrons/MeV is the collected light yield expected for two squared APDs on one crystal. Thus, taking into account the long-term APD bulk current recovery, after 10 years of running at LHC, $I_B = 32 \text{ nA}$ is expected, which yields a noise contribution of $\sim 200 \text{ MeV}$ on a 3×3 crystal sum, right at the acceptable level. From the global APD characteristics in Table 1 it can be seen that characteristics for both manufacturers are not far from the optimum requested for the CMS ECAL. The APD surface area shall be increased to 0.5 cm^2 . Likely, two squared APDs per crystal will be used. This shall allow to keep the noise increase with irradiation

at an acceptable level for an optimum ECAL performance. Operation at $14^{\circ}\text{C} - 18^{\circ}\text{C}$ could also help reducing the dark current and is being considered.

Vacuum phototriodes are the best candidates as end-cap photodetectors, since they work well at small angles to the magnetic field, and offer a sufficient resistance to the high radiation environment expected at large η values.

5 Calibration and monitoring

(a) For a non-radiation hard crystal, LASER monitoring response and electron shower response versus radiation dose (left), and correlation between LASER monitoring response and electron shower response (right).

(b) Energy deposition spectrum in a sum of 3×3 crystals for 280 GeV electrons.

Figure 5: Results from beam tests in 1997.

A precalibration of all the crystals in a high-energy electron beam at two energies is foreseen. Each supermodule (or Dee) will be already equipped with a monitoring system using injected LASER light. Since it has been established that radiation only affects the crystal transparency, light injection shall allow to monitor changes in calorimeter response. The correlation between response to beam particles and monitoring system will be established at that level. In situ, an absolute calibration using physics events (mainly $Z \rightarrow ee$) will be performed, depending on luminosity, every 1 to 5 weeks to achieve the ultimate detector performance ($\sim 0.5\%$ constant term).

Studies have been performed in beam tests, using a LASER at two different wavelengths (one emitting red the other green light). A particularly radiation-soft crystal has been irradiated, and its change in response to electromagnetic showers has been compared to the LASER monitoring response. One observes on the left part of Fig. 5(a) the decrease of the signal with radiation dose, as well as the decrease of signal due to the LASER light. On the right side of Fig. 5(a) the correlation is plotted between the crystal response to electromagnetic showers and its response to the monitoring light. Particularly in the range of high values (0.95 to 1.) expected during operation of the calorimeter the correlation is nicely linear and can thus be exploited for an accurate tracking of the effect of radiation on the crystals.

6 Performance studies on crystal matrices in 1997

6.1 Beam tests on a 7×7 crystals matrix

Monitoring studies as well as studies of intrinsic properties were performed in 1997 on a 7×7 crystal matrix, using one APD per crystal, and conventional read-out electronics, with preamplifiers + line drivers bringing the signals along 80 m cables into Lecroy fastbus ADCs. The crystal dimensions corresponded to the projective shape at $\eta = 0$ of the barrel, including the 3° tilt with respect to the pointing direction. Temperature and voltage were stabilized and the crystal calibration was monitored with LASER light injected via optical fibres from the front face of the crystals. The tests made use of the SPS H4 beam line of the CERN North area. Besides the mentioned monitoring studies, the crystal energy resolution was studied up to an unprecedented energy of 280 GeV. The corresponding energy deposition spectrum in a sum of 3×3 crystals is shown in Fig. 5(b). No high-energy tails are observed, and thus no sign of rear leakage, which would cause direct signals in the APDs. Taking into account the fluctuations in beam momentum due to synchrotron radiation, $0.2\% < \sigma/p < 0.32\%$, one obtains a energy resolution compatible with the prediction, $\sigma/E = 0.38\%$, from a fit to the data at lower beam energies.

Figure 6: Distributions of energy resolution values and its fit values measured for 21 different arrays of 3×3 crystals equipped with one APD each.

The distribution of energy resolutions at 120 GeV for 21 different sums of 3×3 crystals yields an average $\sigma/E = 0.53\%$ (Fig. 6(a)). A fit of the energy resolution values as a function of beam energy yields for the same 21 sums of 3×3 crystal arrays a distribution of constant terms centered around 0.34% (Fig. 6(c)) and of stochastic terms with an average of 4.2% (Fig. 6(b)). This last number will be reduced further through the use of 2 APDs per crystal.

6.2 Prototype '97 (6×6 crystals)

An ECAL pre-prototype has been built, consisting of 36 crystals ($\eta = 0$ geometry) in an Al+fiberglass alveolar structure with nominal dimensions, arranged in 2×6 cooled subunits. Temperature and voltage are stabilized, and the crystal calibration monitored with light injection via optical fibres. The aims are to test the entire electromechanical arrangement and to evaluate the front-end performance. The prototype includes capsules with one APD per crystal and preamplifiers with linear, multiple gains. A circuit called Floating Point Unit (FPU) selects the appropriate gain range for each 25 ns sample and multiplexes them into a single ADC input. A commercial 12-bit 40 MHz voltage sampling ADC is used (Analog Device AD9042). The resulting digital word consists of a 12-bit mantissa and a two-bit code indicating which gain stage was used. A digital, optical link follows towards the higher level read-out and data-acquisition.

A full coverage of the dynamic range has already been demonstrated, and an electronic noise has been measured of 4500 e for a 120 pF APD capacitance. The ADC linearity was measured to be better than 0.1%, and it has proven to be radiation hard beyond $3.3 \times 10^{13} \text{ n/cm}^2 + 2.2\text{Mrad}$. This system is now being evaluated in all its aspects.

7 Conclusions

The CMS ECAL has reached its final R & D phase, and its target performance has been demonstrated in beam tests. It has been shown that the LASER monitoring system can track crystal response changes of 5% and beyond. A complete electronics chain with the required performance has been produced, and a system test of 36 channels is being performed. A sufficient radiation resistance has been reached for all detector elements (crystals, APDs and all the readout elements). In 1998, preproduction runs for crystals will be performed. The production characteristics for the photodetectors will soon be defined. The Technical Design Report is being written, and is due end of 1997.

References

- [1] CMS Technical Proposal, CERN/LHCC 94-38 (1994).
- [2] R. Chipaux, O. Toson, CMS Technical Note CMS TN / 95-126 (1995).
- [3] R.-Y.Zhu, C.Woody *et al.*, Proc. VI International Conference on “*Calorimetry in High Energy Physics*”, Ed. A. Antonelli *et al.*, Frascati Physics Series (1996).
- [4] F. Cavallari *et al.*, CMS Note 1997/030 (1997) and private communication.
- [5] Y. Benhammou *et al.*, CMS TN/96-052 (1996).

List of Figures

1	Longitudinal section of the electromagnetic calorimeter (one quadrant).	2
2	Progress on radiation hardness for chinese crystals in 1997.	3
3	Progress on radiation hardness for russian crystals in 1997: relative light output loss versus dose for full size russian crystals measured as the total photocurrent on a hybrid PMT during front irradiation with ^{60}Co at 0.15 Gy/h.	3
4	APD behaviour after neutron irradiation (From Ref. [4]).	5
5	Results from beam tests in 1997.	6
6	Distributions of energy resolution values and its fit values measured for 21 different arrays of 3×3 crystals.	7

List of Tables

1	Characteristics of Avalanche Photodiodes	5
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