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The CMS electromagnetic calorimeter Overview and status report

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Abstract

An overview status is given of the Lead Tungstate electromagnetic calorimeter which is being developed for the CMS detector at LHC.

This includes the development status of $PbWO_4$ crystals, the mechanical design of the calorimeter, the read-out and a brief look into results from test measurements in particle beams.

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The CMS electromagnetic calorimeter

Overview and status report

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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 $80 \text{ GeV} < m_H < 130 \text{ GeV}$, 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. Lead Tungstate crystals R&D

Beyond the known benefits of a homogeneous calorimeter, $PbWO_4$ has been chosen as a crystal for various reasons. Its scintillation emission is fast, with a main light decay component $\tau \sim 10 \text{ ns}$. It is a crystal with a short radiation length X_0 of 0.92 cm and a small Molière radius $R_M = 2 \text{ cm}$, enabling thus the construction of a very compact calorimeter. At the time of the decision which type of electromagnetic calorimeter to adopt for CMS, substantial production capabilities existed already. This crystals can relatively easily be grown from readily available raw materials. Compared to other crystals, like BGO, it has a modest light yield, but this drawback can be overcome by using photodetectors with some gain. Recent progress in the production of large Silicon

avalanche photodiodes (APDs), which are suited to work in magnetic fields, were the encouraging factor.

Radiation hardness is an important concern, since the radiation levels expected at LHC integrated over 10 years of high luminosity operation (for a total $\int \mathcal{L} dt = 5 \times 10^5 \text{ pb}^{-1}$) are considerable. Between 0.5 Mrad at $\eta = 0$ and 7 Mrad at $\eta = 2.6$ have been calculated [1], along with total neutron fluences between $2 \times 10^{13} \text{ n/cm}^2$ in the barrel and $10 \times 10^{13} \text{ n/cm}^2$ at the high η end of the end caps.

It has since a long time been established that radiation hardness is intrinsic to $PbWO_4$ crystals, however full size crystals are affected by radiation at different levels. The vanishing effect of neutrons on the crystal behavior has been confirmed by measurements, which can be found in Ref. [2]. Under photon irradiation, the scintillation mechanisms are not affected, and indeed no change of shape is observed in the crystal emission spectrum [3]. Indirect evidence is also observed in the energy resolution measured with a high-energy (120 GeV) electron beam, which yields consistent values $\sigma/E = 0.5\%$ between before and after irradiation of the crystal. Nevertheless, with photon irradiation, a reduction of light output is observed, due to the formation of colour-centres, which induce some absorption in the crystal. This kind of effect can be expressed through and induced absorption coefficient μ_{ind} (expressed in m^{-1}). While early samples showed induced absorption coefficients with values around 4 m^{-1} ,

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(a) in a crystal grown by Czokralski method.

(b) in a crystal grown by Bridgeman method.

Figure 1. Induced absorption coefficient (m^{-1}) in a crystal, as a function of light wavelength, at various time intervals after irradiation.

values that stay below $0.5 m^{-1}$ have recently been reached in full-size crystals grown using both, the Bridgeman and the Czokralski growth methods, as can be seen in Figs. 1(a) and 1(b).

Correspondingly, irradiation only induces a loss of 5 to 8% of transmitted light in the crystal, which is at a tolerable level for the CMS ECAL, especially since the effect saturates at low dosis (~ 1 krad) [4], and the recovery time is of the order of several days. The loss of transmission due to irradiation can then be monitored as foreseen through a light injection system in the calorimeter, and corrections can be applied. However, it has to be ensured that consistently no fast recovery is present, since it would be hardly monitored. The present aim is to verify that batches of crystals with no fast recovery can be produced in a reproducible way.

Concerning mechanical processing, it has been demonstrated that with the chosen new technology the mechanical tolerances of processed crystals can be considerably improved. In the distribution of the difference between actual and nominal lateral dimensions, the RMS value has been reduced from $320 \mu m$ to $40 \mu m$. Moreover, the

maximum observed deviation from the nominal value was $180 \mu m$, to be compared to $1 mm$ in 1995. From these results it seems possible to reach the required tolerances of $^{+0}_{-200} \mu m$ in crystal dimensions needed for the CMS ECAL construction.

Towards the end of 1995 a sizeable improvement in light yield had been reached in $PbWO_4$ crystals. Unfortunately, along with this increase, a slow component of unacceptable level was observed in the scintillation light (up to 5% left after $1 \mu s$). The main mechanism leading to such a slow component was later understood, in that some traps in the crystals were slowing down the usually very fast (picoseconds) recombination of the free carriers which yield the green luminescence. It was shown that Molybdenum impurities were the main cause of this effect: after reducing the contamination with Molybdenum by a factor 10, the slow component was considerably reduced.

Initially, the reduction of the presence of Molybdenum also caused a loss of light yield, since the Molybdate group is very efficient in transferring trapped electrons to green lumines-

(a) Collected light yield, zero suppressed, in the photodetector as a function of distance.

(b) Effect of light yield uniformity on the energy resolution for electrons hitting the center of 3×3 crystal arrays centered around four different crystals.

Figure 2. Energy resolution fits for electrons hitting the center of 3×3 crystal arrays centered around four different crystals.

cence centers. However, a large effort to reduce non-radiative traps associated to defects allowed to gain back the previously obtained light yield values.

Also the optical transmission of the crystals has been improved, in particular in the region of scintillation, between 450 and 550 nm. Thus the intrinsic self-absorption has decreased, so that the yield of collected light has increased even further, to values over 100 photons/MeV.

One further characteristics in crystals is the collected light yield as function of distance from the photodetector. Two concurrent effects participate in the shape of this quantity: the crystal transparency and the focussing effect due to the tapered crystal shape. Some examples are shown in Fig. 2(a).

To avoid affecting the energy resolution, this profile has to be flat in the region where the electromagnetic showers have their maximum. This region is indicated in the plots of Fig. 2(a) by two vertical lines. Indeed, a correlation has been observed between this characteristics and the fitted energy resolution for 3×3 crystal arrays with those crystals at their centers. The fitted energy resolution plots are visible in Fig. 2(b). Clearly, the two crystals with a steep light yield profile in the shower maximum region, also have considerably larger constant terms in the fitted energy resolution curves. This is thus a parameter which will have to be controlled in the detector construction.

Figure 3. Electron energy resolution fits for various sampling readout configurations for a sum of 5 crystals in a cross.

3. Photodetectors

For the detection of the $PbWO_4$ scintillation light, Silicon Avalanche Photodetectors (APDs) have been chosen, due to their suitable characteristics. They are in fact insensitive to magnetic fields, allowing thus operation in the 4 Tesla CMS solenoidal field, they also have some internal gain, as needed with the modest light yield produced by the crystals. Additionally, their quantum efficiency matches well the $PbWO_4$ emission spectrum. However, several APD parameters have to be optimized, and this is 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, the so-called Excess Noise Factor [5] which quantifies the fluctuations in the multiplication process, the gain stability with respect to temperature and voltage, and the response to ionizing radiation hitting the diode. An extensive discussion of the characteri-

zation and all the progress reached so far in APD development for the CMS ECAL can be found in Ref. [5]. Concerning the resistance to radiation, it is now established that the APD behaviour corresponds to that of Silicon. Dark current measurements after irradiation show a dark current I_D recovery. Extensive studies of this kind have started, and these data will then be convoluted with the expected LHC operation profile, to obtain a realistic calculation of the evolution in time of I_D , and thus of the total expected noise profile. Since the dark current is strongly temperature dependent, operation at a lower temperature (e.g. 16°C) than initially assumed will be considered.

A further object of R&D will be the optimization of the light collection. This can be achieved by improving the entrance window optics. Also an increase of active area per crystal is being considered, in the investigation of affordable scenarios.

4. Front-End R&D

At LHC, a front-end readout system is needed that can cover a dynamic range of ~ 50 MeV to ~ 2 TeV, with a sampling frequency of 40 MHz. Since the front-end is planned to be placed behind the crystals, compactness and radiation hardness are crucial.

A readout system capable of meeting these requirements has been built and tested by a collaboration of several institutes, namely U. of Lyon, Princeton University, ETH Zürich and PSI Villigen. The test setup made use of the SPS X3 beam line at CERN, which yields 4 to 50 GeV electrons, and it consisted of a 3×3 matrix of modest quality crystals, equipped with Hamamatsu APD's (120 pF capacitance), which allowed to collect 1 p.e./MeV. The readout system, which was contained within a depth of 15 cm behind the crystals, consisted in its primary configuration of the elements described below, while a more extensive description of all tested configurations can be found in Ref. [4]: A full-range preamplifier in $0.8 \mu\text{m}$ BiCMOS technology, which had two outputs, of gain 1 and 8, each followed by two amplifiers of gain 1 and 4. A circuit followed (Floating Point Unit, FPU) that selects the ap-

Figure 4. Monitoring studies performed in 1995 beam tests.

appropriate gain range for each 25 ns sample, by capturing the multisclope outputs of the preamplifiers and by multiplexing them into a single ADC input. A commercial 12-bit 40 MHz voltage sampling ADC was used (Analog Device AD9042). For reference, a buffered copy of one preamplifier output was sent into a charge ADC.

A preliminary evaluation of the test data show that energy resolution values are obtained which are consistent between the sampling ADC readout and charge integrating ADCs. Since it was not possible to have all nine channels working in the matrix for all tested configurations, a comparison of energy resolutions between different readout configurations is shown for a sum of 5 crystals arranged in a cross (see Fig. 3).

The full needed dynamic range was covered, and a noise of 4000 electrons for a 120 pF APD

capacitance was measured.

The AD9042 ADC was tested to have a linearity better than 0.1%. Its radiation hardness was tested with equivalent doses of 2.2 MRad $+2.7 \times 10^{13}$ n/cm². No change in performance was observed at these doses.

Further developments foresee DMILL versions of the BiCMOS preamplifier and FPU, and tests in high energy beams will continue next year with a larger pre-prototype matrix.

5. ECAL calibration and monitoring

While it is foreseen to precalibrate the entire CMS ECAL detector in an electron beam, the final calibration will be performed *in situ* using physics processes. Depending on luminosity, this needs a running time of 1 to 5 weeks. [1]. Between

Figure 5. Typical time evolution (in $^{\circ}\text{C}$) of a crystal temperature in 1996.

such calibration periods, it is foreseen to track the time evolution of the calorimeter response by measuring its temperature map and by monitoring the crystals transparency. Namely due to the fact that only the transparency is affected by radiation, it is possible to use a light injection system to follow its evolution. Several methods are under study, the most promising one being a LASER light pulses injection system via optical fibres at 2 or 3 different wavelengths. A discussion of preliminary studies are presented at this conference, in Ref. [6]. Monitoring studies have already been performed in 1995 and 1996 on a crystal matrix used for beam tests. Figure 4(a) shows on the left side the time evolution of a crystal response for beam events and injected LED light pulses. Their plotted ratio tends to settle to a constant. This ratio is not expected to be equal to unity, due to the differences in the emission spectrum and in the light collection between scintillation and LED light, however, after using the LED monitoring data to apply a correction to beam events, the remaining fluctuation (Fig. 4(b) mirror ex-

actly the measured fluctuations in temperature (Fig. 4(c)) of the crystal. This fact allows to confidently say that no other ununderstood fluctuations are present. Moreover, due to an improved cooling system in the crystal matrix used for tests in 1996, the temperature fluctuations are considerably reduced, to less than 0.1°C peak-to-peak with respect to 1995 (Fig. 5), leaving no room for large response fluctuations.

6. ECAL mechanical design

Figure 6. Prototype design of an alveolar sub-module containing 2×6 crystals.

The mechanical structure of the CMS ECAL has to deal with several constraints, given by the fragility of the more than 100000 crystals and by the need for a temperature regulation of crystals and photodetectors, of course taking into account the calorimeter size and complexity, which has moreover to be hermetic. Concerning inter-crystal gaps, this requirement is being met by tilting the crystals by 3° with respect to the direction pointing towards the center of the detector.

The supporting structure is being designed using thin, high tensile-strength, low-Z materials, and keeping the highest possible modularity.

The smallest subunit is designed to be an alveolar submodule of 2×6 fiberglass submodules to individually contain the crystals, with a reflective coating on the inner walls, yielding less than $500 \mu\text{m}$ intercrystal gaps. A sketch of an alveolar submodule is visible in Fig. 6. The front-end readout will be contained in a capsule mounted at the back of each crystal.

Baskets made out of Carbon-fiber composite are foreseen as modules for assembly and installation, containing 48 or 60 alveolar submodules each. They would lead to intercrystal gaps at the basket boundary of less than 6 mm. It is the basket structure which is designed to take the cantilever of the submodules.

Finally, supermodules consisting of several baskets held by a U-shaped spine at the outer ECAL radius shall be used for calibration and installation. The critical region of transition from barrel to end cap is being optimized to allow the best possible passage for the inner detector services and cables, while preserving the detector hermeticity. Also the details of the ECAL front plate are being refined, to allow the passage of optical fibres for the ECAL light monitoring system.

7. Conclusions

The characteristics of crystals steadily improve towards the required performance. Avalanche photodiodes have reached an optimum in their intrinsic parameters. A proof-of-principle has been given for a full dynamic-range readout system responding to the speed requirements at LHC, based on a multilinear front-end. The mechanical design is being developed as a modular structure built out of low-Z, high tensile-strength materials. Altogether one can conclude that the development of the CMS electromagnetic calorimeter has remarkably progressed over the last year.

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