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The CMS ECAL project – Overview and status report

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Abstract

An overview is given of the Lead Tungstate ($PbWO_4$) electromagnetic crystal calorimeter for the CMS detector at the Large Hadron Collider (LHC) at CERN in Geneva. This includes a description of the engineering design, the development of the calorimeter components, the read-out system and results obtained in particle beams.

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For the CMS Collaboration

1 Introduction

The CMS collaboration is preparing a high-precision electromagnetic calorimeter (ECAL) for its detector. Its conception is based on the need to optimise the discovery potential of a light Higgs, with a mass $m_H < 150$ GeV, decaying into two photons. Since the natural width of such a Higgs 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 1.24 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 units. These submodules will carry a reflective inner coating, yielding inter-crystal gaps of < 500 μ m. Forty or fifty such submodules (depending on η) are foreseen to be assembled into Aluminium baskets, 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 precalibration in the test beam and installation. Hermeticity has been optimised by tilting the crystal axis by 3° 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 as smallest units identical “supercrystals” containing 6×6 crystals, 22 cm long (owing to the presence of a $3 X_0$ thick preshower detector in front) and with 24.7×24.7 mm² front face dimensions. The front face of the calorimeter shall be at 3170 mm distance from the detector centre along the beam axis, and the crystals will be tilted by 3° with respect to the direction pointing towards the centre of the detector for hermeticity. A support structure is foreseen here with the supercrystals cantilevered off the front side of “Dee”-shaped, thick Aluminium plates. All readout electronics, from the preamplifier to the fiberoptics readout, is to be sited on the rear of the support plates. The endcap ECAL covers the pseudorapidity region $1.48 < |\eta| < 3.0$.

3 Crystal Development

The development of Lead Tungstate crystals of a quality suitable for use in the CMS ECAL has been pursued with manufacturers in Bogoroditsk, Russia, and China (Shanghai Institute of Ceramics, SIC, and Beijing Glass Research Institute, BGRI). A detailed discussion on the progress made in this development can be found in Refs. [2] and [3]. The intrinsic properties of Lead Tungstate crystals have been thoroughly tested in the laboratory and in beam tests, and many results can be found in Ref. [1] and in several publications [4], [5]. Figure 1 summarizes the excellent energy resolution that can be reached at electron energies as high as 280 GeV, as measured in the SPS test beam at CERN. The spectrum shows no low-energy tails, indicating a good shower containment, and no high-energy tails, whose presence would hint to rear shower leakage leading significant interactions of ionising particles in the photodetector material. Moreover, taking into account the fluctuations in beam momentum due to synchrotron radiation, $0.2\% < \sigma/p < 0.32\%$, one obtains an energy resolution compatible with the prediction, $\sigma/E = 0.38\%$, from a fit to the data at lower beam energies.

The most critical issue in crystal development is their radiation hardness. The environment for the CMS ECAL is particularly hostile in this respect. At the highest design luminosity of 10^{34} cm⁻²s⁻¹ one expects, at the electromagnetic shower maximum, dose rates between 0.18 Gy/h at $\eta = 0$ and 0.29 Gy/h at $\eta = 1.5$, and values up to 15 Gy/h at $\eta = 3$ in the ECAL end caps. 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 [6], while a sample-dependent effect is observed with photon irradiation. It has been shown that the scintillation mechanisms

Figure 1: Energy deposition spectrum in a sum of 3×3 crystals for 280 GeV electrons.

is not damaged, nor is the scintillation emission spectrum changed [7]. 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 is 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. Extensive R&D work has been carried out to improve the crystal radiation hardness through the optimisation of raw materials purity, of stoichiometry, through doping and post-growth treatments in gaseous atmospheres (so-called annealing) [8].

Concerning crystal production in Bogoroditsk, the first two batches of preproduction crystals (200 in total) have been received. A very good yield of 100 crystals delivered from 108 ingots grown was reached already with the first batch, delivered on September 4, 1998, while a second batch was just received a few days prior to this conference, on November 3, 1998. Some final R&D is still ongoing, to further optimise the radiation hardness through improved doping conditions, while a total of 50 ovens are in continuous operation there for production and R&D. Some growth tests were performed for the production of the larger cross-section end-cap crystals, with 25 of them produced, but further R&D is needed for an optimised yield.

In China the R&D efforts are continuing for the production of crystals with good radiation hardness properties. The efforts were concentrated there as well on all aspects of crystal growth, where progress was aimed at in steps, with the successful production of 5 cm long, extremely radiation hard crystals [8], progressing then to 10 cm long radiation resistant samples [9] and now working on full-size crystals. In parallel, SIC is preparing the infrastructure for mass production, through the development of multiple crystal furnaces, where 10-crystal furnaces are already operational and two 28-crystal furnaces are being constructed, along with cutting and polishing machines.

The CMS ECAL group is preparing two regional centers for the reception of the nearly 84000 crystals, their characterisation and the assembly of the calorimeter, one at the ENEA Laboratory in Rome and one at CERN. For the crystal processing, automated crystal control systems have been constructed, one in each regional center, which allow following operations: The automatic processing of crystals in sets of five mounted in racks to be further used for storage and gluing of the photodetector capsule, the measurement of crystal dimensions by a standard 3D machine, light yield and transverse transmission measurements at several locations along the crystal (uniformity) and a longitudinal transmission measurement. With each crystal identified by a bar code, all this information is conveyed into an ObjectivityTM database via a distributed process control system, C.R.I.S.T.A.L. [10], [11]. The two machines which were constructed, while having the same functionality, differ in their realisation and the way the light yield is measured, for the CERN machine (ACCOS) from a decay time spectrum [12] and for the machine in Rome (ACCOR) from the pulse height spectrum of a ^{60}Co radioactive source.

Figure 2: Design of the two Avalanche Photodiodes and their mechanical capsule mounting on a crystal.

4 Photodetectors and Readout

For the detection of the PbWO_4 scintillation light in the ECAL barrel, Silicon Avalanche Photodiodes (APD) have been chosen, since they are insensitive to magnetic fields, thus allowing 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 the PbWO_4 emission spectrum. However, several APD parameters had to be optimised, and this has been the object of extensive R&D efforts pursued by manufacturers like EG&G and Hamamatsu, in collaboration with several institutions participating to the ECAL project. The crucial parameters there are the APD capacitance, the so-called Excess Noise Factor which quantifies the fluctuations in the multiplication process, the gain stability with respect to temperature and voltage, and the response to ionising radiation hitting the diode (typically expressed as an effective thickness). Recently, the ECAL group has selected Hamamatsu photodiodes, mainly for their reliability, and presently a consolidation of characteristics is being pursued. An extensive discussion can be found in Ref. [13]. In the construction of the CMS ECAL, two 25 mm^2 APDs per crystal shall be used, as can be seen in Fig.2. This shall allow to keep the noise increase with irradiation at an acceptable level for an optimum ECAL performance.

Recently, the electro-mechanical layout of the front-end readout has been redesigned. The photodetectors and the temperature sensor (see Fig. 2), which sit on the crystal, have a negligible power dissipation, but crystal and APD need to be in an environment where the temperature is stable to less than 0.1°C . The front-end readout electronics elements add up to approximately 1 W/channel power dissipation, but do not need a very stable thermal environment. The new design accommodates them into two thermally separate zones to satisfy these demands, with short cable links between the two, whose performance is being evaluated by prototypes.

Figure 3: Floating-point readout for the CMS ECAL.

Figure 4: For 9 different, radiation-soft crystals superimposed, monitoring response versus shower response for 523 nm (green) light injection.

The readout for the CMS ECAL has to work at 40 MHz, to match the 25 ns bunch crossing time of the LHC. The front-end part of the readout (see Fig. 3) foresees, for each channel, a Floating Point Preamplifier (FPPA), which yields $\times 1$, $\times 4$, $\times 8$, $\times 32$ amplifications and which selects the highest gain range without saturation for each 25 ns sample and multiplexes them into a single 12-bit ADC input, so that the needed 16 bit dynamic range can be covered. A commercial 40 MHz voltage sampling ADC is used, from Analog Devices, 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 readout and data acquisition. The ADC linearity was measured to be better than 0.1%, and 500 of them were irradiated and proven to be radiation hard beyond $3.3 \times 10^{13} \text{ n/cm}^2 + 2.2 \text{ Mrad}$. All these elements of the readout chain are mounted on a 5-channel readout card, with the possibility of test pulse injection. Two cards are then sandwiched together to form a readout unit which matches a 10-crystal submodule.

While the readout single channel layout will be adopted for the end caps as well, some modification may be needed to accommodate the different subunit (the “supercrystal” in this case) structure. Concerning photodetectors, vacuum phototriodes are the best candidates for the end-caps, 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, with 1” such devices already produced.

5 Calibration and Monitoring

A precalibration of all the crystals in a high-energy electron beam at two energies is foreseen. Each supermodule (or Dee) will be equipped by then with a monitoring system using injected LASER light. Since it has been established that radiation only affects the crystal transparency, light injection shall allow us 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 $Z \rightarrow e^+e^-$) will be performed, depending on luminosity, every 1 to 5 weeks, to achieve the ultimate detector performance. The goal being an intercalibration better than 0.4%, a complete map of all crystals (precision $< 0.3\%$) will require 35 days during low luminosity running, at $10^{33} \text{ cm}^{-2}\text{s}^{-1}$. A light injection system will be used with green LASER light at a wavelength around 500 nm. At this wavelength it has been shown, through beam tests on radiation-soft crystals, that the signals measured for electromagnetic showers and the signals for injected LASER light are linearly correlated, with consistent slopes between crystals, as can be seen in Fig. 4.

It has also been demonstrated in a prototype beam test using the sampling readout, that a LASER signal shape, as transmitted through the FPPA, can be achieved that is consistent with the one obtained with beam particles.

6 Preshower

At startup of CMS, a preshower detector will be present in front of the ECAL end caps, to allow the separation of π^0 from single photons. The preshower detector will cover the pseudorapidity region $1.65 < |\eta| < 2.6$, and will have two layers of absorber ($2X_0 + 1X_0$), each followed by a plane of silicon detectors. Each silicon detector will

be $63 \times 63 \text{ mm}^2$ in size, with 2 mm pitch strips, for a total of 4500 detectors, to be thermally controlled to -5°C . On each side of it, a 4 cm thick moderator will allow to keep the neutron flux below $1.6 \times 10^{14} \text{ neutrons/cm}^2$ for 10 years of running. Beam tests have allowed to show that, for particle energies above 60 GeV, the degradation of ECAL energy resolution due to the presence of the preshower detector is negligible [5].

7 Conclusions

The CMS ECAL is now in the preproduction phase. Some R&D is still being performed, to consolidate the quality of the detector elements subject to the highest demand in terms of stability and radiation resistance. Substantial progress was made in the simplification of the mechanical design. All the elements needed for detector construction exist and their required performance was demonstrated with beam and laboratory tests. The preparation of regional centers and their infrastructure is well advanced, so that detector construction can soon ramp up to the scheduled rhythm.

References

- [1] The CMS Collaboration, “The Electromagnetic Calorimeter Project”, Technical Design Report, CERN/LHCC 97-33 CMS TDR 4, CERN, Geneva, Switzerland, 1997.
- [2] P. Lecoq *et al.*, paper N4-1 at this conference.
- [3] S. Baccaro *et al.*, paper N4-3 at this conference.
- [4] G. Alexeev *et al.*, “Studies of lead tungstate crystal matrices in high energy beams for the CMS electromagnetic calorimeter at the LHC”, Nucl. Instr. Meth. **A385** (1997) 425-434.
- [5] E. Auffray *et al.*, “Beam tests of lead tungstate crystal matrices and a silicon strip preshower detector for the CMS electromagnetic calorimeter”, Nucl. Instr. and Meth. **A 412** (1998) 223-237.
- [6] R. Chipaux, O. Toson, CMS Technical Note CMS TN / 95-126, CERN, Geneva, Switzerland (1995).
- [7] R. Y. Zhu, “A study of the properties of lead tungstate crystals”, Nucl. Instr. Meth. **A 376** (1996) 577.
- [8] H. F. Chen, K. Deiters, H. Hofer, P. Lecomte, F. Nessi-Tedaldi, “Radiation Damage Measurements of Undoped Lead Tungstate Crystals for the CMS Electromagnetic Calorimeter at LHC”, Nucl. Instr. Meth. **A 414** (1998) 149.
- [9] H. F. Chen, K. Deiters, H. Hofer, P. Lecomte and F. Nessi-Tedaldi, “Measurements of PbWO_4 crystals behaviour under irradiation”, Proc. Int. Workshop on Lead Tungstate Crystals, Rome (Italy, October 1998), ETH Preprint ETHZ-IPP PR-98-07 (Zürich, Switzerland).
- [10] A. Bazan *et al.*, poster N20-30 at this conference.
- [11] J.-P. Peigneux *et al.*, poster N20-31 at this conference.
- [12] M. Moszynsky and B. Bengston, “Light pulse shapes from plastic scintillators”, Nucl. Instr. Meth. **142** (1977) 417.
- [13] G. Organtini, paper N11-3 at this conference.