The CMS Lead Tungstate Electromagnetic Calorimeter

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Abstract. The CERN LHC will open a new regime in the exploration of fundamental interactions. Of central importance to these studies will be the precise measurement of high energy electrons and photons. The CMS experiment therefore incorporates a high resolution electromagnetic calorimeter comprising 76000 lead tungstate crystals, covering almost $4\pi$, and capable of operating reliably for ten years in a very hostile environment. The detector design is presented, together with beam measurements demonstrating that the goal for energy resolution of better than 0.5% above 100 GeV can be achieved.

1. Introduction
CMS (Compact Muon Solenoid) [1] is a general purpose detector nearing completion for operation at the CERN LHC. A key design feature is the high resolution electromagnetic calorimeter (ECAL), comprising ~76000 lead tungstate crystals covering almost $4\pi$ of solid angle. The benchmark that has been used to set the design goals of the ECAL is the potential to discover a Higgs boson in the mass region below 130 GeV, by measuring the decay $H \rightarrow \gamma\gamma$. For a low mass Higgs, the intrinsic decay width is very small. Thus the measured width, which has a crucial influence on the significance of the signal above the expected large background, comes entirely from the ECAL energy resolution.

To achieve its goals, the ECAL must be reliable, fast, have high granularity and be radiation resistant to lifetime (~10 years) doses amounting to 4 kGy and $2\times10^{13}$ n/cm$^2$ in the Barrel and up to 50 times higher in the Endcaps. In addition, it must contribute to the first level trigger.

2. The Crystal Calorimeter
The CMS ECAL comprises a Barrel section and two Endcaps (figure 1). The Barrel is divided into two halves, each divided into 18 $\phi$-sectors (‘Supermodules’) containing 1700 crystals. Each Endcap is divided vertically into two ‘Dees’, each with 3660 crystals grouped in 5x5 sub-units (‘Supercrystals’). All crystals are tapered and are arranged in a projective geometry, pointing approximately $3^\circ$ away from the mean beam collision point, to minimise the effect of inter-crystal gaps. A Preshower detector, consisting of two orthogonal planes of silicon strip sensors interleaved with lead; improves $\gamma/\pi$ discrimination in the Endcap regions. In order to minimise the amount of inert material between the crystals and the collision region, the entire calorimeter is located within the magnetic field volume of the CMS 4 T superconducting solenoid.

Lead tungstate [2] has a short radiation length (0.89 cm), and a small Moïlère radius (2.19 cm). This permits a design that has high granularity combined with compactness, a very important consideration for a detector located within the magnetic field volume. Scintillation emission is fast (80% of light within 25 ns) and peaks in the blue (425 nm), simplifying photo-detection. However, the light yield is rather low (~50 photons/MeV), and varies with temperature (-2%/C at $18^\circ$C). Thus
the photo-detectors must have internal gain (in a strong magnetic field) and the temperature of the calorimeter must be stabilised to better than 0.1°C. Furthermore colour centres form and self-anneal under irradiation at room temperature, causing the light output to vary with dose rate. A very precise system for monitoring crystal transparency is therefore required. Barrel crystal production is complete and Endcap crystals are now being delivered. There are two sources: the Bogoroditsk plant in Russia (~900/month) and the Shanghai Institute of Ceramics in China (~130/month).

In the Barrel section, the photo-detectors are Avalanche Photodiodes (APDs) [3], specially developed by Hamamatsu Photonics for CMS. They are each 5x5 mm² in area and are mounted in pairs. They have a quantum efficiency of 75% and are operated at a gain of 50. In the Endcaps, where radiation levels are higher and the magnetic field direction is within 25° of the crystal axes, Vacuum Photo-Triodes (VPTs) are deployed [4]. VPTs are photo-multipliers with a single gain stage and these particular devices were specially developed for CMS by RIE, St Petersburg. They are 280 mm² in effective area, with 20% quantum efficiency and have a radiation resistant UV glass window. They have a typical gain of 10 at 4 T.

The on-detector electronics [5] incorporates ASICs implemented in IBM 0.25 µm technology. The photo-detector signal is processed by a 40 ns shaping preamplifier, followed by three parallel amplifiers with gains of 1, 5 and 12, providing a dynamic range of 20 000. A multi-channel, 12-bit ADC digitises the three signals at 40 MHz and the largest unsaturated value is selected. The data are buffered and then transmitted through 0.8 Gb/s optical links to the off-detector electronics on receipt of a Level-1 Trigger. The on-detector electronics also calculates trigger primitives from the digitised data and transmits them through dedicated fibres to the Level-1 trigger. The noise per channel, measured in a test beam, is equivalent to ~40 MeV. The cluster noise scales as √n, where n is the number of crystals in the cluster.

Changes in crystal light yield under irradiation are tracked with a laser monitoring system [6]. Normalisation is provided by a system of very stable PN diodes. Changes in optical transmission measured with a blue laser (440 nm) are strongly correlated with changes in the yield of scintillation light under irradiation, allowing precise corrections to be made (figure 2). The light pulses are distributed through a system of optical fibres. An optical switch directs laser pulses to one of 88 calorimeter regions, and a two stage distribution system in each region delivers light to each crystal. The laser will be pulsed during the beam gap that occurs every 89 µs during the LHC beam cycle. The entire ECAL will be scanned every 20 minutes.

3. Inter-calibration
In 2006, nine supermodules were inter-calibrated with high energy electrons (90 and 120 GeV), in a geometrical configuration that reproduced the incidence of particles during CMS operation. One of the supermodules was exposed to the beam on two occasions, separated by an interval of one month.
The resulting sets of inter-calibration coefficients are in close agreement, the distribution of differences having an rms spread of 0.27%, indicating a reproducibility of 0.2% for the individual measurements.

All 36 supermodules were commissioned in turn by operating them on a cosmic ray stand for a period of about one week. A muon traversing the full length of a crystal deposits an energy of approximately 250 MeV, permitting inter-calibration information to be obtained for the barrel ECAL. A comparison of the cosmic ray and high energy electron data demonstrates that the average precision of the cosmic ray inter-calibration is 1.5%.

The ultimate inter-calibration precision will be achieved in situ with high energy electrons and photons from physics events.

4. Energy Resolution

Energy is measured by summing over a cluster of crystals, typically 3x3 or 5x5, surrounding a central crystal. The response varies with the point of impact in the central crystal, mainly because the shower extends laterally beyond the cluster boundary. A correction can be made for the variation of response with shower position, using information from the crystals alone. When this correction is applied, good resolution is obtained for incident points distributed over the full front face of a crystal (figure 3).

![Figure 3. Energy resolution versus energy, after applying the impact-position correction.](image1)

![Figure 4. Energy resolution for electrons with impact points simulating the situation in CMS.](image2)

To simulate the situation in CMS, where impact points are distributed randomly within crystals and across crystal boundaries, a series of test beam runs were taken with central impact points distributed at representative positions, including crystal edges and corners. After correction, the results show that the design goal of better than 0.5% resolution at high energy is met (figure 4).

References

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