The CMS crystal calorimeter for the LHC

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Abstract

The CMS crystal calorimeter, comprising about 80,000 scintillating lead tungstate crystals read out by avalanche photodiodes (in the barrel) and vacuum phototriodes (in the endcap) is designed to give excellent energy resolution in the demanding LHC environment. It is now entering the construction phase. A status report on the project is presented, including recent results from test beam verification, crystal production and photodetector development.

I. INTRODUCTION

The Compact Muon Solenoid (CMS) experiment will build a general-purpose detector designed to exploit the physics of proton-proton collisions at a centre-of-mass energy of 14 TeV over the full range of luminosities expected at the LHC. The CMS detector is designed to measure the energy and momentum of photons, electrons, muons, and other charged particles with high precision. The detector is designed around a 6 m diameter, 4 T, superconducting solenoid, inside which sit both the hadronic and the electromagnetic calorimeters.

One of the CMS design objectives has been to construct a very high performance electromagnetic calorimeter. The electromagnetic calorimeter (ECAL) will play an essential role in the study of the Higgs sector, with the capability to detect a light Higgs (m_H<150 GeV/c^2) through the two-photon decay mode, and measure the electrons from the decay of Ws and Zs in the channels $H\rightarrow ZZ^*$, $H\rightarrow ZZ$ and $H\rightarrow WW$ for $140<m_H<700$ GeV/c^2. The ECAL will also be important for a large variety of Standard Model and new physics processes.

A homogeneous ECAL using high density scintillating crystals results in a very compact, high performance calorimeter which enhances the $H\rightarrow\gamma\gamma$ discovery potential. Table 1 details the expected Gaussian contributions to the energy resolution (i.e. not including tails from conversions and bremsstrahlung in the tracker material, and geometric edge effects) [1]. The noise figures assume reconstruction in 25 crystals, and includes contributions from both electronics and pile up.

Table 1
Contributions to CMS ECAL energy resolution

	Barrel	End cap
Stochastic term	2.7%/√E (E in GeV)	5.7%/√E (E in GeV)
Constant term	0.55%	0.55%
Noise		
Low luminosity	E_T = 155 MeV	E_T = 205 MeV
High luminosity	E_T = 210 MeV	E_T = 245 MeV

II. MECHANICAL STRUCTURE

The calorimeter comprises about 80,000 23 cm long ($26X_0$) scintillating lead tungstate crystals, each having a front face measuring a little more than 2 x 2 cm^2, which are held in light, rigid alveolar structures. The scintillation light is read out by avalanche photodiodes (in the barrel) and vacuum phototriodes (in the end cap). Together the barrel and end cap sections provide precision electromagnetic calorimetry over the pseudorapidity interval $|\eta| < 2.5$.

A pre-shower device is placed in front of each end cap to enhance neutral pion rejection in that region. The pre-shower detector consists of two planes of lead absorber instrumented by two planes of silicon strip detector (strip pitch 1.8 mm), with a total thickness of $3X_0$.

The mechanical organization of each half barrel section consists of 18 identical supermodules. Each supermodule contains 17 crystal shapes (corresponding to 17 regions in η) and is made up of four modules. The modules contain either 400 or 500 crystals and are made up of submodules based on alveolar structures housing 2x5 crystals. The crystal axes are off-pointed from the vertex point by about 3° in both η and φ. The two end caps are made up from 4 identical 'Dees'. Each 'Dee' is constructed from an x-y array of identical 'supercrystals', alveolar structures each of which houses 5x5 identical crystals. The end cap crystals are also off-pointed from the vertex.

The whole ECAL is maintained at a stable temperature using two active cooling systems: one to extract the heat generated by the electronics and a second to maintain the crystals and APDs within a tight temperature tolerance.

III. CRYSTAL PRODUCTION

Results from the first batches of pre-production crystals from Russia are very encouraging. The yield of good crystals, satisfying the optical and mechanical specifications, is progressively improving and approaching the desired value. The crystal producers in China have concentrated on setting up the infrastructure needed for production and have brought into operation two 28-fold pulling furnaces.

By June of this year a major milestone was achieved with the delivery of one thousand pre-production crystals from Russia. The production of all the required crystals is expected to take five years. The setting up of infrastructure at the centres where the crystals will be assembled into modules for installation is well advanced.

Two major issues for the crystals that have had to be tackled are the longitudinal uniformity of light collection and radiation hardness. The effect of longitudinal non-uniformity has been studied with shower Monte Carlo simulation and the predictions verified in the test beam. To keep the constant term contribution from longitudinal non-uniformity < 0.3% we require that the slope of the light collection curve in region of shower maximum is less than 0.35%/X_0. This can be achieved for barrel crystals by requiring the producer to depolish one long face to a specified roughness. This, in turn, requires that the inside of the alveolar pocket structures have a highly reflective coating to avoid significant light loss. In the end cap the crystals are less tapered and have a larger cross-section, and adequate uniformity is obtained without special crystal treatment.

The radiation hardness of crystals has been studied over a number of years, and we have seen a continuous series of improvements. These steps and improvements were covered in more detail by other talks in the session [2]. Since radiation has been shown to affect only the transparency of the crystals (by causing the formation of color centers), the resulting small changes can be monitored by injected light pulses.

A sophisticated light monitoring system is designed to inject 440 nm laser light pulses (15 ns FWHM) into each individual crystal to measure the optical transmission at a wavelength close to the scintillation peak. The system allows the monitoring of short-term changes in the crystals' light transmission, and hence allows the correction of the small changes of transparency induced by radiation. A programme of tests is establishing the detailed performance of this system.

IV. READOUT

The photo-detectors have to operate in a 4T magnetic field. In the barrel Avalanche Photodiodes (APDs) are used. Two 25 mm^2 APDs are glued to the rear face of each crystal. They are operated at a gain of 50, and have the advantage that the effective thickness, in which any charged particles leaking from the rear of the shower can liberate charge which is multiplied by the gain, is small (~8µm). The type of avalanche photodiode has been chosen after evaluation of several hundred samples from two industrial suppliers, and in September of this year an order was placed for 120,000 devices.

In the end cap silicon devices become unsuitable as the expected neutron flux increases rapidly. Vacuum phototriodes (VPTs) are used. These are devices in a 1-inch diameter glass case achieving a gain of 8 in a slightly off-axial magnetic field.

Table 2 summarizes the key parameters of the photodetectors.

Table 2
Key parameters of the photodetectors

	APD	VPT
Active area	2 x 25mm^2	~300mm^2
Quantum efficiency (420 nm)	70%	18%
Capacitance	2 x 70 pF	A few pF
Operating gain	50	8 (4T)
Excess noise factor	2.0 (M = 50)	2.5 – 3.0
dM/dV (M=50)	3.3%/V	< 0.1%/V
dM/dT (M=50)	2.2%/°C	< 1%/C
I_D after 2x10^{13} n/cm^2	2µA	-

Scintillation light from the crystals is converted to a current by the photodetectors and shaped to a voltage pulse by the preamplifiers. The voltage pulse is digitized at 40 MHz by a floating point ADC. A 2^{17} dynamic range is achieved using a 12-bit ADC and four ranges. The digital values are transmitted to the counting room on high-speed optical links (one link per crystal). The front-end electronics must all tolerate a harsh radiation environment — up to 100kGy and 10^{14} n/cm^2 for ten years LHC running in the end cap. The complete front-end power consumption is a little over 1 W per channel. The final design of the complete, radiation hard, electronics chain is nearly complete.

Currently a complete, fully functional, 400 channel prototype module is under construction, using crystals that pass stringent quality criteria, and a full radiation hard electronics chain.

V. TESTBEAM RESULTS

By the end of 1997 we were achieving consistently good results with test matrices in electron beams (σ/E (E = 100GeV) < 0.6%). This was the result of control of longitudinal uniformity, increased light output from crystals, control of the temperature stability and improved APDs. The focus since then has shifted to testing realistic prototypes with more or less final mechanical structures and electronics, and various specialized tests.

The prototypes tested in 1999 have performed well. Figure 1 shows the energy reconstructed in barrel prototype matrix in August 1999 when a 280 GeV electron beam is incident. The matrix consists of three 2x5 crystal sub-modules equipped with twin-APD photodetector capsules. The excellent resolution, σ/E = 0.40%, includes a significant contribution (0.24%) from synchrotron radiation fluctuations of the beam momentum.

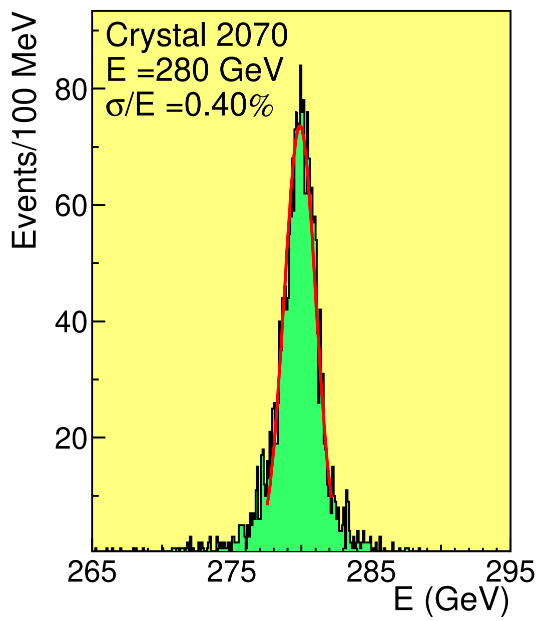

Figure 1: Reconstructed energy with 280 GeV electrons incident on barrel prototype matrix.

An end cap prototype matrix was also tested this year. It consisted of a 'supercrystal' of 5x5 crystals equipped with 1 inch VPTs. Figure 2 shows the energy reconstructed when 180 GeV electrons were incident on this matrix. This is the response of the bare crystal matrix. In the CMS detector the end cap crystals sit behind a silicon strip preshower device. A result from tests with a preshower prototype placed in front of the supercrystal matrix is shown in Figure 3. The response of the crystals alone and of the final reconstructed energy, using the preshower data, are shown in the left and right histograms respectively.

An important use of results from tests with the preshower detector is the verification of Monte Carlo shower simulations of the combined preshower and crystal system. Figure 4 shows a comparison of the resolution as a function of energy obtained in the test beam with the predictions from a full simulation. The results are in excellent agreement.

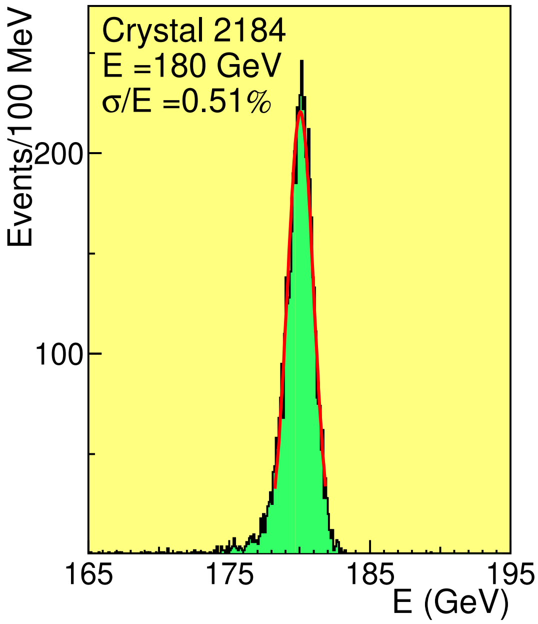

Figure 2: Reconstructed energy with 180 GeV electrons incident on the bare end cap prototype matrix.

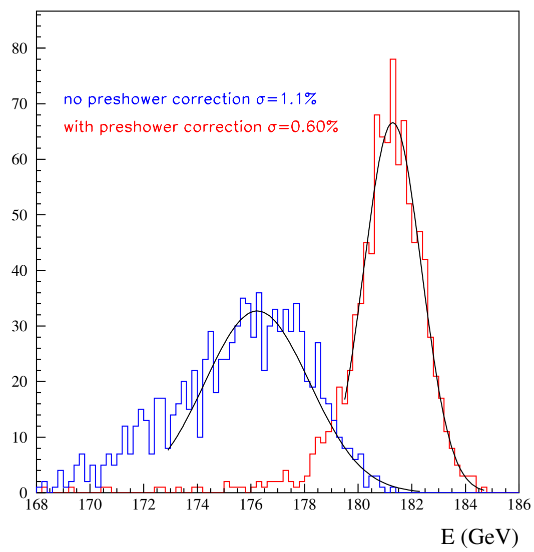

Figure 3: Reconstructed energy with 180 GeV electrons incident on the combined end cap and silicon strip preshower prototype.

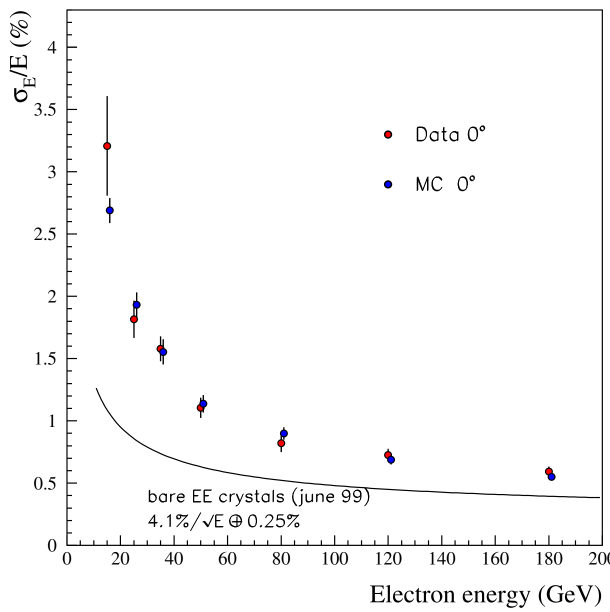

Figure 4: Energy resolution as a function of energy. Comparison of data with Monte Carlo shower simulation.

VI. Summary

Five years of intensive R&D on the CMS electromagnetic lead tungstate crystal calorimeter have resulted in a design that can meet the challenging LHC requirements. Mass production of crystals is underway, and the APDs have been ordered — this signals the start of the construction phase.

IX. Acknowledgments

I gratefully acknowledge the help of the CMS ECAL collaboration in collecting the material to make this summary.

X. References

[1] Technical Design Report for CMS Electromagnetic Calorimeter, *CERN/LHCC 97-33*, p23, December 1997.

[2] P. Lecoq, Scintillator Developments for High Energy Physics and Medical Imaging, (paper presented at this conference).

X. Qu, L. Zhang, R. Zhu, Radiation Induced Color Centers and Monitoring in Situ for Lead Tungstate Crystals, (paper presented at this conference).