The Compact Muon Solenoid Experiment

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The CMS electromagnetic calorimeter: status, performance with cosmic and first LHC data

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Abstract

The Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC) is ready for first collisions. Electrons and photons clean identification and excellent energy and momentum resolution are crucial at LHC in several fields. They are essential in at least two of the Higgs decay channels, they can be signatures of the decay of new heavy bosons, they play a role in Supersymmetry and are of course central in the reconstruction of electroweak and QCD processes. Therefore a key design feature of the experiment is ECAL, the high resolution electromagnetic calorimeter made of 76,000 lead tungstate crystals. The design goal for ECAL is the potential to discover a neutral Higgs boson in the low mass region by measuring the decay into two photons. For a low mass Higgs the intrinsic decay width is very small, therefore the measured width precision is dominated by the ECAL energy resolution. This has led to a target energy resolution of 0.5%. The design and performance of the CMS ECAL with test beams, cosmic rays, and first beam dump events at the LHC in 2008 will be presented. In addition, the status of the calorimeter and plans for calibration with first collisions will be discussed. CMS ECAL is ready for exciting physics with LHC and design goals are within reach.

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THE CMS ELECTROMAGNETIC CALORIMETER STATUS: PERFORMANCE WITH COSMIC AND FIRST LHC DATA

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The Compact Muon Solenoid (CMS) detector at the Large Hadron Collider (LHC) is ready for first collisions. The main physics goal of the experiment is the search for the Higgs boson and new particle phenomena. If the Higgs mass is lower than 150 GeV, the Higgs electromagnetic decay into two photons is the cleanest channel for discovery. In this mass range the signal lies over an irreducible background and this demands a high resolution e. m. calorimeter. The design and performance of the CMS e.m. calorimeter (ECAL) with test beams, cosmic rays, and first LHC beam events in 2008 will be presented. The status of the calorimeter and plans for calibration with first collisions will be discussed. CMS ECAL is ready for exciting physics and design goals are within reach.

1. Introduction

The CMS (Compact Muon Solenoid) detector ¹ is a multipurpose apparatus that will take data at the LHC at CERN. Electrons and photons clean identification and excellent energy and momentum resolution are crucial in several fields. They are essential in at least two of the Higgs decay channels, they can be signatures of the decay of new heavy bosons, they play a role in Supersymmetry and are of course central in the reconstruction of electroweak and QCD processes. Therefore a key design feature of the experiment is ECAL, the high resolution electromagnetic calorimeter made of lead tungstate crystals. For a low mass Higgs the intrinsic decay width is very small, therefore the measured width precision is dominated by the ECAL energy resolution. The potential to discover a neutral Higgs boson in the low mass region by measuring the decay into two photons has been much used as a benchmark for ECAL performance. An energy resolution ² of 0.5% for testbeam electrons above 100 GeV has been measured.

With a crystal calorimeter having a small stochastic term ($\sim 3\%$) the limiting factor for excellent resolution at high energy is the constant term. In particular the CMS ECAL aims to reach an intercalibration precision of better than 1%.

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2. The CMS Electromagnetic Calorimeter

The CMS electromagnetic calorimeter (ECAL) ² is a hermetic, homogeneous, fine granularity e.m. calorimeter comprising about 76,000 lead tungstate (PbWO_4) crystals, arranged in a central barrel (EB) and two endcaps (EE) in a quasi pointing geometry to the interaction point to avoid cracks aligned with particle trajectories. The crystal length in the barrel is 230 mm corresponding to 25.8 radiation lengths. The total crystals volume is 11 m^3 and the weight is 92 t. The barrel calorimeter is organized into 36 supermodules each containing 1,700 crystals while the endcaps consist of two dees, with 3,662 crystals each.

The ECAL detector should be compact to fit inside the CMS superconducting solenoid magnet. For the light collection the crystals are equipped, in the barrel, with Hamamatsu avalanche photodiodes (APD, two for each crystal) insensitive to the 4T magnetic field and vacuum photo-triodes (VPT), in the endcaps, insensitive to the expected high radiation level and able to operate in a magnetic field almost parallel to their axis.

Installation of EB into CMS was performed during 2007. The EE dees were constructed and installed during 2008 and the entire EB and EE calorimeters were commissioned prior to the closure of CMS in late August 2008 in preparation for first LHC beam. The silicon pre-shower endcap detectors were instead installed more recently, and will be fully commissioned prior to beam in 2009.

3. Crystal Properties

The main features of PbWO_4 scintillating crystals are high density ($\delta=8.28 \text{ g/cm}^3$), extremely short radiation length and Molière radius ($X_0=0.89 \text{ cm}$, $R_M=2.2 \text{ cm}$), allowing the realization of a homogeneous compact calorimeter. It produces fast signals, 80% of the light is emitted in 25 ns, but major drawbacks are the reduced light yield (100 photons per MeV) that requires the use of a photo-detector readout system with internal gain; a strong light yield dependence from temperature ($-2\%/^\circ\text{C}$ at about 18°C) which impose a cooling system to stabilize the crystals and photo-detectors temperature to $\pm 0.05^\circ\text{C}$; and a high refractive index that makes the light extraction difficult.

An intense R&D program has been carried out to ensure mass production of optically clear and radiation hard crystals. Ionization radiation produces a loss of light transmission without changes to the scintillation mechanism. The damage can be tracked and corrected for by monitoring the optical transparency with injected laser light.

Most of the crystals have been produced in Russia with a small contribution from China. The production rate has been about 10,000 crystals/ year.

4. Read-out Electronics

To provide the desired resolution over the full energy range of signal events, the readout system should measure energies in a wide dynamic range (between 50 MeV and 2 TeV), should be fast to minimize pile-up of events, have low power consumption and should use radiation hard components. In order to minimize external noise contributions most of the readout chain must be mounted directly inside the detector. This has also the advantage of reducing the number of optical links to the off-detector readout.

The on-detector electronics has been designed to read 5x5 crystals, forming a trigger tower (supercrystal) in the EB (EE). The signals from photo-detectors are pre-amplified and shaped by an ASIC (the Multi Gain Pre-Amplifier) chip which consists of three parallel amplification stages with nominal gain 1, 6 and 12. Each of the three analog outputs are digitized in parallel by a multi channel 40 MHz, 12 bits ADC, with an integrated logic that selects the highest not saturated signal. A time window of 10 samples is readout for every L1 Trigger. The electronic noise is less than 40 MeV/channel. All front end ASICs were developed in 0.25 μm technology, intrinsically radiation hard. On each group of 25 crystals, trigger primitives are generated and sent to the Off-detector electronics.

5. General Performance

All supermodules were fully tested in the laboratory after construction and were exposed to cosmic rays for a period of one week to obtain initial channel to channel intercalibration constants. Nine of the 36 supermodules were also tested with electron beam in the 15-250 GeV energy range to provide absolute energy calibration and detailed performance studies.

The energy resolution can be parameterized as a function of the incident electron or photon energy E , in GeV, as in Eq. (1):

$$\sigma/E = S/\sqrt{E} + N/E + C \quad (1)$$

where S represent the stochastic term which depend on event by event fluctuations in lateral shower containment; N represents the noise term depending on the level of electronics noise and event pile-up; C the constant term which depends on non-uniformity of the longitudinal light collection, leakage of energy from the rear side of the crystal and accuracy of the detector intercalibration. The energy resolution parameters: $S= 2.8 \%$, $N=120 \text{ MeV}$; $C=0.3\%$; have been measured at the electron test beam and are well within design specifications^{3,4}.

6. Energy and Time Reconstruction of Electrons and Photons

The first step in the ECAL cosmic data analysis is the reconstruction of the signal amplitude and time for each crystal. A fit is performed on the 10 individual

time samples using a parameterized pulse shape function, with fixed shape parameters optimized separately for barrel and endcaps crystals. The baseline pedestal value is estimated from the first three digitized samples. The use of alternative amplitude and pulse timing reconstruction methods, including a digital filtering technique (the baseline method at LHC), have been studied.

97% of the shower produced by unconverted photons is contained in a 5x5 matrix of crystals in the η , ϕ plane. In order to reconstruct the photon energy one must account for lateral leakage due to the staggering, which increases with η .

The conversion of the individual channel response to the incident particle energy requires several steps, each introducing some conversion factor. The signal amplitudes obtained for each crystal have to be multiplied by an intercalibration coefficient and then a cluster algorithm selects the channels to be summed. At this stage an overall factor must be applied to the sum of energies depending on the clustering algorithm and including containment corrections, but taking into account also the dependence of response on the impact position, particle type etc. Finally an overall scale factor provides the right absolute energy scale.

Excellent reconstruction of unconverted photons can be achieved measuring the energy in a 5x5 crystal matrix around the seed crystal.

In CMS about half of the photons convert into electron pairs in the Tracker material in front of ECAL. For electrons the situation is complicated by the production of bremsstrahlung photons. Because of the magnetic fields these photons will deposit their energy in the calorimeter in the form of clusters along the ϕ coordinate and should be included using an appropriate clustering algorithm.

7. Calibration and Monitoring

7.1. Validation of Intercalibration Constants

One of the main problems of a precision calorimeter is the calibration of the channels. The associate uncertainty directly contributes to the constant term.

An essential issue in CMS is therefore the ECAL channel response uniformity as this contributes directly to the overall energy resolution. This uniformity is determined by the accuracy of the calibration of the relative response or intercalibration, between different channels across the detector.

The unconverted photons deposit on average 70% of their energy in a single crystal. The main sources of channel to channel response variations are the crystal light yield variation in the barrel (about 13%), and the gain spread of the photo-detectors in the endcaps (about 25%), both measured during construction. To reduce this spread and provide already an acceptable performance of the detector at startup, different calibration procedures have been adopted during the construction and commissioning phase of ECAL. In particular an intercalibrati-

on accuracy⁵ of 0.3% is available at startup for the 9 EB supermodules exposed to electron test beam. In addition all supermodules have been commissioned in turn on a cosmic ray stand. Intercalibration coefficients with an accuracy better than 1.5% for most of the volume and raising to about 2% at the barrel outer end ($\eta > 1.5$) have been derived. There was not enough time to intercalibrate EE on a cosmic stand. In this case the intercalibration coefficients at startup were available with an accuracy of about 10-15% derived from laboratory measurements of crystal light yield and photo-detector response. The use of “beam splashes” data taken during the LHC run in 2008 improves this accuracy to about 7%.

Calibrations with events collected during LHC operation are the main tool to achieve the target intercalibration precision of better than 1% required for the detection of the $H \rightarrow \gamma\gamma$ decay. In addition also the energy scale and linearity of response must be precisely calibrated. In situ fast equalization at 1.5-2% can be obtained exploiting the ϕ symmetry of the detector in the energy deposition of minimum bias events. In the long term, intercalibration can be obtained by comparing the energy and the momentum of the electrons from W decays; absolute calibration can be obtained by studying the reconstructed mass of $Z \rightarrow e^+e^-$ events. Rapid calibration has been shown to be possible using π^0 mass reconstruction. We should achieve the target intercalibration with only a few pb^{-1} of data.

7.2. Crystal Transparency Monitoring

Another important issue is how well we can track changes in crystal transparency. This is affected by radiation damage in a way that depends on the dose rate and the crystal characteristics. It is estimated that transparency will decrease by 1-2 % at 10^{33} luminosity and that there will be no appreciable change in transparency in the barrel for data taking expected in 2010, although small changes may be observable in the endcaps. Fast recovery takes a few hours.

Damage and recovery are monitored by laser light injected into each crystal through optical fibers. Blue light (440 nm) is used to track response, infrared light (796 nm) provides a check. During normal operation ECAL acquires 3 types of non physics events: pedestals, electronic test-pulses and laser shots. These monitoring events are acquired during the LHC abort gaps: the LHC filling scheme has an interval of 118 bunch crossing (2.95 μs) where there are no particles, the so called abort gap, which may be used to dump the beam. An optical switch directs light to one half supermodule or one quarter dee in turn. It takes about 20 minutes to run the full calibration sequence. The laser monitoring

system has been used in all test beam activities and during all stages of commissioning achieving a monitoring stability of 0.02%.

8. ECAL Performance in Global Runs

Global runs started early in 2007, first with only the data acquisition system itself, and then grew up to include almost all CMS at the end of August 2008.

CMS ran in global mode a few days per week and a full week per month logging more than 350 million cosmic triggers in the period March-August 2008.

8.1. Performance in LHC Beam Runs

On September 10, 2008, LHC injected beam in the accelerator and in the following days CMS saw clear beam related signals. In particular during the ring commissioning LHC dumped on purpose the beam (10^9 protons at 450 GeV) several times into closed collimators placed 150 m upstream of CMS creating a huge number of secondary particles travelling horizontally and therefore very useful to commission forward detectors. We estimate that about 300,000 muons reached ECAL at the same time dumping about 200 TeV of energy: more than 99% of channels fired. These “beam splash” events have been extensively used to internally synchronize ECAL (to better than 1 ns) and also to improve the intercalibration of the endcaps channels.

8.2. ECAL Cosmic Runs at Four Tesla (CRAFT)

ECAL is designed to measure energy shower deposition up to 1.5 TeV therefore is not optimized to detect the energy released by a cosmic ray (a m.i.p. crossing a crystals releases 250 MeV). However increasing the gain of the photodetectors in the barrel from 50 to 200, it's possible to clearly see a signal and trigger on it.

The energy deposit depends on track length inside the crystal active volume. Since cosmic muons are reaching ECAL with all possible angles there is not a real peak but more a continuous shoulder. In addition cosmic muons can also deposit quite high energy via catastrophic bremsstrahlung photon emission.

Cosmic muons have therefore been used to commission many aspects of ECAL. By studying their arrival time we were able to measure the time difference between the top and bottom part of the detector. An asymmetry in the occupancy along the y axis is seen since low energy muons reach ECAL preferentially along the shaft used to lower CMS into the underground cavern.

The aim of CRAFT was to run CMS for four weeks during 2008 fall with all subsystems participating, collecting data continuously to further gain operational

experience before data taking with p-p collisions. A major goal was to operate CMS at full field (3.8 T) for as much of running period as possible and to study the effect of the magnetic field on the detector components.

Figure 1. ECAL stopping power dE/pdx as a function of the muon momentum. The points correspond to data from CRAFT muon events; the curve is the expected stopping power of lead tungstate crystals from literature (it is not a fit). The dashed curve shows the contribution from collision loss and the dashed line shows the contribution from bremsstrahlung.

We collected more than 370 million cosmic events. The fraction of channels that were operational was 98.33% in EB and 99.66% in EE. It is expected that the fraction of EB channels operational for the first collisions will exceed 99%.

Much really useful information has been extracted from these data. The study of energy deposition in ECAL crystals is one of such analysis. We studied the stopping power of the CMS electromagnetic crystal calorimeter as a function of the muon momentum as measured in the Tracker. In Figure 1 we see good agreement between the measured and the expected $PbWO_4$ stopping power.

9. Conclusions

CMS ECAL is more than ready for first LHC collisions data.

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