Frascati Physics Series Vol. XL (2006), pp. 77–86
FRONTIER SCIENCE 2005, NEW FRONTIERS IN SUBNUCLEAR PHYSICS
Milano, 12-16 September, 2005

THE ELECTROMAGNETIC CALORIMETER OF THE CMS EXPERIMENT

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Abstract

The Electromagnetic Calorimeter of the CMS experiment is made of about 75000 Lead Tungstate scintillating crystals. This project aims to achieve an extreme precision in photons and electrons energy measurement. General motivations, main technical challenges, performances achieved and the actual status of the project will be discussed in the following.

1 Introduction

The Large Hadron Collider will allow the study of pp interactions at a center of mass energy of 14 TeV. The main physics goals of the CMS experiment [1] are the discovery of the Higgs boson and the search for new physics phenomena, in particular the appearance of particles predicted by Supersymmetric theories. The maximum design luminosity foreseen at LHC is 10^{34} cm^{-2} s^{-1} and the bunch crossing rate will be 40 MHz. With the total cross-section $\sigma_{pp} = 80$ mb on average 20 events will be produced in one crossing corresponding to about 1000 tracks. The radiation environment is expected to be severe, in ten years of running (meaning a total integrated luminosity of 5x10^5 pb^{-1}) detector parts will be exposed to a neutron fluence as high as 10^{17} n/cm^2 and γ doses of 10^6 Gy. The typical signal to background ratio for intresting physics events is O(10^{-10}). These extreme conditions imposed a long R&D phase to obtain high granularity, fast, radiation resistant and selective detectors.

The electromagnetic calorimeter of the CMS experiment [2)] is composed of 75848 Lead Tungstate ($PbWO_4$, about 90 t) crystals organized in a barrel (61200 crystals) covering the central rapidity region $|\eta| \leq 1.48$ and two end-caps which extend the coverage up to $|\eta|=3$. A pre-shower detector placed in front of the end-caps improves the γ - π^0 separation in this region. To obtain the most hermetic coverage the barrel has a nearly pointing geometry both in ϕ and η (crystals have a 3° tilt away from the interaction point in both directions). The scale of this detector is one order of magnitude higher than any crystal calorimeter built in the past, e.g. L3 calorimeter (about 10000 BGO crystals) operated at LEP [3)] and the complexity as well.

2 The Challenges

Crystal calorimeters have an excellent energy resolution, the best attainable in electromagnetic calorimetry. The Higgs boson hunt in the ”low mass” region is the basic ground for the CMS choice to build a crystal calorimeter. All the precision tests of the Standard Model performed by LEP experiments indicate a low mass Higgs [4)]. In the mass interval 100 - 150 GeV the Higgs boson can be favorably detected by its decay in two photons. The H$\rightarrow \gamma\gamma$ reaction is not the most abundant but the cleanest one for detection in spite of the large irreducible background. The natural width of a Higgs in this mass region is of the order of few MeV making the resolution on the invariant mass of the two photons completely determined by the energy and angular resolution of the calorimeter. Thus the discovery potential is set by the experimental resolution and H$\rightarrow \gamma\gamma$ is a benchmark reaction for this instrument.

The energy resolution of a calorimeter can be parameterized by:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt(E)} \oplus \frac{b}{E} \oplus c \qquad (1)$$

where a is the stochastic term related to any kind of Poisson-like fluctuation, b is the electronic noise term and c the so-called constant term. The target values for the coefficients in eq.(1) are a = 0.027 $GeV^{1/2}$, b $\leq$0.2 GeV and c $\sim$ 0.005 with an angular resolution $\sigma(\theta) \sim \frac{50mrad}{\sqrt{E(GeV)}}$. With these values a Higgs boson with a mass of 120 GeV could be detected by the CMS experiment with significance S = 5 collecting 30 fb^{-1} at luminosity 10^{33} $cm^{-2}s^{-1}$.

The precision experimentally attainable depends on a long list of instrumental effects which should be taken into account and kept under control. A crystal calorimeter is a very precise instrument that requires a tremendous effort to be finalized.

2.1 Lead Tungstate (PWO)

Lead tungstate ($PbWO_4$) is a very dense ($\rho = 8.28$ g/cm^3) scintillating material. The most appealing properties of PWO crystals are the small radiation length (X_0 = 0.89 cm) and the small Moliere radius (R_M = 2.2 cm) which allow the construction of a compact and granular calorimeter, the fast scintillation light decay time (80% of light is emitted within 25 ns) and the basic radiation resistance. Nevertheless this material presents a few drawbacks. The low level of the light yield (100 photons/MeV, $\sim$ 0.2% with respect to NaI:Tl) requires that the light be read-out with a photo-detector able to amplify the signal, the high refractive index (2.29 at peak emission wavelength λ = 420 nm) makes the extraction of light from the crystal very difficult and finally the strong dependence of the light yield on temperature (-2%/°C around 18°C) requires a strict control and a system to avoid temperature variations exceeding 0.1°C.

A huge effort was done during R&D to improve the light yield of these crystals without spoiling their fast response and to guarantee their radiation hardness at a level sufficient to preserve the requested energy resolution. The radiation hardness of PWO and its optimization [5)] was one of the major problems to be overcome to allow the use of these crystals at LHC. At a radius of 1.29 m, corresponding to the front of the calorimeter, a γ dose rate of 0.15 Gy/h is expected at $\eta = 0$, while in the end-caps the dose rate can be as high as 15 Gy/h. PWO crystals are damaged by electromagnetic radiation through the creation of color centers that reduce their transparency. The scintillation mechanism remains untouched. The amount of the damage depends on the dose rate and reaches a stable level after a small administered dose. The observed loss of light measured on production crystals irradiated with γ at 0.15 Gy/h is quite closely distributed around 3% for all crystals. The maximum accepted loss is set to 6%. This loss is tolerable and can be followed with a monitor system by injecting light through the crystals. Once irradiation ends, a partial recovery of crystal transparency happens in few hours.

After a pre-production of 6000 barrel crystals (whose dimensions depend on η but are approximately of 2 cm x 2 cm x 23 cm) to optimize growing techniques and quality, the mass production of high and uniform quality started in year 2001 in Bogoroditsk plant (Russia).

A dedicated R&D was needed to obtain end-caps crystals due to the larger (with respect to barrel) transversal dimensions: $\sim$ 3 cm x 3 cm. Few hundreds of these crystals have been produced to tune quality and optimize assembly procedures.

To maintain some flexibility in the production, after a process of validation of the quality, a small fraction of barrel and one half of end-cap crystals has been assigned to Shanghai Institute of Ceramic (SICCAS, China).

More than 75% of barrel crystals have been produced and tested.

2.2 Photo-detectors and read-out electronics

Avalanche photo diodes (APD) were developed for the barrel part of the calorimeter [6]. These devices are insensitive to the 4 T magnetic field of the experiment. Their quantum efficiency around the wavelength of the PWO emission peak is about 75%. The amplification is produced in a small region ($d_{eff} \sim 6\ \mu$m) of very high electric field obtained with heavy doped silicon layers. To be operated in CMS, APD internal gain is set to M = 50. Two APDs of 25 mm^2 area are coupled to each crystal. In this configuration about 4000 photo electrons are produced per GeV of deposited energy. APD gives contributions to all terms in the energy resolution (1). In particular the gain stability is directly related to the constant term c. The variation of gain with bias voltage 3.1%/V and temperature -2.4%/°C made mandatory the development of a very stable bias system and to maintain temperature changes of the system below 0.1 °C. APDs have been developed and optimized with an extensive R&D program, the production in Hamamatsu Photonics (Japan) ended in 2004.

In the end-caps region radiation levels are too high to use APDs, the longitudinal magnetic field allows there the use of vacuum photo triodes (VPT) [7]. These are single stage photo-multiplier tubes with a fine metal grid anode. Their active area is 280 mm^2, quantum efficiency is about 20% at 420 nm and a gain of 8 - 10 is expected in the 4 T magnetic field. The irradiation produces a loss of optical transmission of the UV glass window that is foreseen to be limited to less than 10% after ten year of LHC running.

The photo-detectors are followed by an on-detector read out electronics. The main properties of this system are the wide dynamic range (50 MeV to 2 TeV), the speed, the trigger capability, and the radiation hardness. The read-out chain is organized in a modular structure made of a matrix of 5 $\times$ 5 channels (trigger tower). Each trigger tower is composed of 1 motherboard, 5 Very Front End (VFE) cards, 1 Low Voltage Regulator (LVR) card and 1 Front End (FE) card. The motherboard distributes the high voltage to the APDs/VPTs and connects them to the 5 VFE cards, which preamplify, shape and digitize the signals with 3 different gains (1, 6, 12) at 40 MHz. The automatic gain switching, together with a 12-bit ADC leads to an effective dynamic range of 15-16 bits. The FE card estimates the tower energy and sends it to CMS Level-1 trigger, while storing the data from the 25 channels in a data buffer during the latency time (3 μs). The optical link system connects at 800 Mbit/s the Gigabit Optical Hybrid (GOH) chips on the FE card to the off-detectors electronics 100 m downstream. On reception of a Level-1 trigger, based on the energy of the trigger tower, the data from the 25 channels are transferred serially to the off-detector electronics. The whole trigger process takes place within 3 μs.

2.3 Regional Centers for assembly and test

The construction of the calorimeter is a distributed process. Parts as crystals, capsules, mechanical elements for the support structure etc. are produced under the responsibility of different Institutions taking part to the project and sent afterwards (barrel parts) in two Regional Centers located in CERN and Rome. The calorimeter has a modular structure. The basic sub-unit of the barrel, composed by a crystal and a capsule (hosting two APDs read in parallel) glued together, is inserted in a glass fiber alveolar structure. Ten sub-units fit in this structure that is closed by an aluminum element and constitute a "sub-module". Sub-modules are of 17 different types depending on η position. A "module" is made by 40 or 50 sub-modules mounted on a 3 cm thick aluminum grid. Modules are of 4 η types. A "super-module" is a set of 4 modules and the barrel consists of two identical halves made by 18 super-modules. End-caps will have a simpler structure, 138 "super-crystals" made of 25 identical crystals are a so-called "dee" and two of them make an end-cap. Endcap crystals production will follow the barrel one and their assembly and test will happen at CERN. All the elements of the calorimeters are assembled and checked step by step, following a well defined quality control protocol to guarantee the perfect functionality of parts resulting from mounting operations. In particular all the crystals are subject to the systematic test of their properties. Both Centers are equipped with similar automatic machines to insure crystal quality [8]. Cooling system and read-out electronics are installed at CERN following an analogously strict quality insurance scheme. The severe control of quality at each step of the construction will insure a fully operational calorimeter at best of its potentiality. The presence of dead or malfunctioning channels in the first 9 super modules fully assembled is less than permill.

3 Key points in energy resolution

At high energy the most dangerous contribution to the energy resolution comes from the constant term c. Beside the uniformity of crystal's light collection which is guaranteed at crystal production level by an appropriate treatment of surfaces [9], key issues to keep the constant term c $\sim$ 0.5% are:

- system stability
- inter-calibration by monitor and physics signals at 0.5% including the effect of radiation damage

3.1 Temperature and APD gain stability

Temperature knowledge and stability is particularly important in the CMS electromagnetic calorimeter system. The temperature dependence of the calorimeter response of -4 %/°C (due to crystals and APDs) imply, in order to achieve the design resolution of 0.5 %, to maintain crystal's temperature stable at 0.05°C. The cooling system designed to this end [10] couples thermally the on-detector electronics cards (VFE), through gap pad and gap filler, to aluminum bars embedding water pipes in order to remove the power dissipated by the electronics ($\simeq$ 2.5 W/channel). Laboratory tests validated the cooling system by measuring the temperature on the crystals with the electronics switched off and switched on. The maximum measured change in temperature was 0.1°C, with a mean change of 0.056°C.

The High Voltage system to bias APDs was designed to keep their gain stable to 10^{-4} ($\pm$30 mV / 400 V) [11] over a period of 3 month. During the acceptance and commissioning of the system, 1224 channels were tested measuring their voltage variation ΔV over a period of one month; 66 mV has been the maximum ΔV measured with the bulk of the distribution around 22 mV.

3.2 Calibration and monitoring crystals transparency loss

The ECAL calibration prior to LHC start-up is crucial both for the detector operation and for the early discovery potential for new physics. The calorimeter channels are mis-calibrated at the level of 10%, due to the intrinsic differences among individual PWO crystals (light yield), quantum efficiency of the photo-detectors and response of the read-out electronics. Before the start-up, three methods will give an inter-calibration of the channels with different precisions. A preliminary inter-calibration of all the crystals is obtained from the crystals Light Yield and APDs laboratory measurements. The comparison of this inter-calibration with the one (very precise) obtained using electron beams shows that the precision achievable with this method is of about 4%. Operating the APDs at gain 200, cosmics rays traversing the crystal along its longitudinal axis collected in about ten days can be used to intercalibrate crystals to about 2-3% [12]. Finally some modules will be calibrated with high energy electron beams to reach a calibration better than 0.5%. This data taking will be mandatory in order to understand: geometrical effects (energy deposition depends on η), effects of gaps between crystals and modules, MC simulation in all its aspects and finally in situ calibration having few regions precisely known.

In-situ ECAL will be calibrated with physics events and a general description of the foreseen strategy can be found in reference [13]. At the beginning of the detector operation a fast inter-calibration method can be used, based on the assumption that in average in minumum bias events the same energy is deposited over a ring of crystals in Φ. A Monte Carlo simulation has shown that the limit of this method is the non perfect Φ symmetry of the detector and that a calibration at the level of about 1-2% can be obtained in the barrel and between 1-3% in the endcaps [14]. The Φ rings can be rapidly inter-calibrated using $Z \rightarrow e^+e^-$ events reconstructing the Z invariant mass. The $Z \rightarrow e^+e^-$ rate is about 1 Hz at low luminosity. The collection of 2fb^{-1} will be enough to obtain an intercalibration at 0.6% [15]. Once the tracker will be fully functional the process $W \rightarrow e\nu_e$ can be used for single crystal calibration. This method minimizes the difference between the measured momentum of the electron track and the energy associated to it in the ECAL. The calibration precision achievable depends on η and for an integrated luminosity of 5 fb^{-1} it may reach 0.5-1.0% in the barrel, the method limit being below 0.5% with higher statistics [16]. The major difficulty in using electrons for ECAL calibration is the presence of an important amount of material due to the "massive" tracker choice made by CMS. Studies are going on looking at π^0 and η^0.

In between calibrations with physics events the evolution of the system due to the loss of transparency induced by radiation damage will be followed with high accuracy by a light injection system. This monitoring system consists of two laser sources, which distribute four wavelengths (440 nm, 495 nm, 700 nm and 800 nm) to each crystal, during the 3 μs long abort gap of LHC, which will be present every 90 μs. The 440 nm light is used to monitor crystals transparency variations, while the 800 nm light will help in monitoring the stability of the electronics response (color centers present in the crystals weakly absorb in this wavelength range). The stability of the laser system has been measured to be better than 0.1 % by means of reference PN diodes. A detailed analysis of the crystal irradiations on beam demonstrated the validity of the relation $S/S_0 = (R/R_0)^\alpha$, where S and R are the signals obtained with the electron beam and with the laser light during irradiation compared to the starting values S_0 and R_0. The crystals (coming from the same producer) are expected to behave in the same way and the fitted exponents of this power law for the different crystals were found to have a spread of 6.3 %, around an average value of $\alpha = 1.55$. By correcting all the crystals for their loss of transparency with the same value of α the follow-up of the calibration coefficients is performed to an accuracy of 0.3 %.

4 Achieved performances

Tests on barrel modules were carried out in 2002 and 2003 [17]. In 2004 a complete supermodule (1700 crystals), built according to the final production specifications, was tested with an electron beam at CERN. This data taking allowed an accurate system test of ECAL and validated the testbeam calibration procedure.

The whole procedure for the energy reconstruction has been investigated. In each crystal the amplitude is reconstructed as a weighted sum of the 10 digitised signal samples, including three samples before the signal, which are used as an estimation of the baseline. By applying the same procedure to data taken with a random trigger, the noise in the single channel has been measured to be about 40 MeV, as expected. In order to study the energy resolution of the calorimeter, electrons in the range between 20 and 250 GeV were collected. The energy resolution measured on 18 towers of 3x3 crystals is in perfect agreement with what expected by design and crystals behave similar way. The average resolution obtained on these crystals is:

$$\frac{\sigma(E)}{E} = \frac{2.9\%}{\sqrt{E}(GeV)} \oplus \frac{0.125}{E} \oplus 0.30\% \tag{2}$$

thus confirming the high performance achivable with this system.

5 Conclusions

The electromagnetic calorimeter of CMS is a challenging project. An intense R&D effort was performed over many years. The calorimeter is actually in the construction phase and the performances of the final system, as measured on test beam, fully satisfy the requirements to made precision physics measurements as needed to detect the rare decay H→ $\gamma\gamma$.

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CMS Documents are available at `http://cms.cern.ch/iCMS`.