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STATUS OF THE CMS ELECTROMAGNETIC CALORIMETER

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On behalf of the CMS ECAL Collaboration

The CMS electromagnetic calorimeter will provide excellent performance (in energy and position measurements) in a very hostile environment (radiation, beam crossing rates). It consists of a barrel made of 61200 lead tungstate crystals each read out by two avalanche photodiodes and of two end caps with 14488 crystals read out by vacuum phototriodes. In early 2002, the front-end electronics was redesigned and is now based on trigger towers that calculate the trigger primitives on-detector at each bunch crossing and transmit raw data upon level-1 trigger acceptance. The status of the calorimeter construction is presented, as well as results of beam tests performed in 2003 using the new electronics scheme, which confirm that the design performance can be reached.

1. Introduction

We present here a general overview of the CMS electromagnetic calorimeter. For more details, please refer to the more specific presentations included in these proceedings^[1-7].

2. Objectives

The main goal of the CMS electromagnetic calorimeter (ECAL) is to measure precisely the energy and the position of e , γ and π^0 . The position and energy resolution benchmark comes from a low mass ($115 < m_H < 100 \text{ GeV}/c^2$) Higgs boson decay to two photons.

The energy resolution can be parameterized as follows

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

where:

- a is the stochastic term which includes contributions from the shower fluctuations, the photodetector statistics and the transverse shower leakage. The aim is to obtain $a \sim 2.7\% \text{ GeV}^{1/2}$ in the barrel.
- b is the constant term which is dominant at high energies and includes the effect of mis-calibrations, non-uniformities of the detector, instabilities in the temperature and high voltage applied to the photodetectors and the rear and front shower leakage. Here the aim is $b \sim 0.55\%$

- c is the noise term due to the electronic noise and incremental dark current from the photodetectors under irradiation. It is also sensitive to pile-up in the detector. The aim is to obtain in the barrel $c \sim 155$ (210) MeV under low (high) luminosity conditions.

To achieve such requirements, the CMS collaboration has chosen to build a homogeneous electromagnetic calorimeter made of lead tungstate (PbWO_4) crystals. This crystal is unique to work in the very demanding LHC environment where:

- the LHC bunch crossing rate is 40 MHz and lead tungstate scintillation is fast (80% in 25ns).
- there is a severe radiation environment and, as the result of R&D, lead tungstate is sufficiently radiation hard.
- compactness (CMS manages to put its entire calorimetry inside its 4T solenoid) and granularity are required, and lead tungstate has a radiation length $X_0 = 0.89$ cm and Moliere radius $R_M = 2.2$ cm.

Unfortunately there are also some drawbacks:

- lead tungstate presents a relatively low light yield hence the photodetector must have some gain.
- its light yield shows a strong dependence on temperature and a very precise cooling system is required.

The photodetectors must be able to work in a magnetic field $B = 4\text{T}$, amplify the signal (required by the low light yield from PbWO_4) and be radiation hard.

3. The barrel

3.1. *Production and data quality control of the crystals*

The ECAL barrel is made of 2 x 18 so called Super-Modules (SM), plus 1 spare SM not intended to be put in the detector, each containing 85 (η) x 20 (ϕ) crystals. The crystals have a tapered shape, which varies slightly with η (17 types). The mean dimensions are 2.2 x 2.2 x 23 cm³.

The crystals are manufactured by the Bogoroditsk Techno-Chemical Plant (BTCP) in Russia. Up to now, 24600 crystals have been delivered out of a total required number of 61200 (not including the 1700 crystals for the 37th SM).

Two regional assembly centers (CERN and INFN/ENEA near Rome) receive the crystals and check the principal characteristics:

- Geometry
- Optical properties (light yield, lateral and longitudinal transmission, uniformity) (Figure 1)
- Radiation tolerance

All the data are recorded in the construction database.

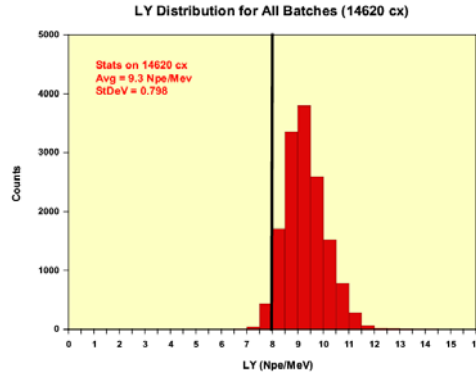


Figure 1: Measurements of light yield of all the crystals received so far at CERN regional center. The black line shows the required specification below which the crystals are rejected.

3.2. The Avalanche Photodiodes (APD)

The CMS APDs are manufactured by Hamamatsu Photonics, Japan. Their main properties are summarized in Table 1.

Table 1: APD properties

Active area	5 x 5 mm ²
Quantum Efficiency	72% at 420 nm
Operating gain (M)	50
Charge collection within 20 ns	99 ± 1%
Capacitance	80 pF
Serial resistance	< 10 Ω
Dark Current (I _d) before irradiation	~ 3.5 nA
Voltage sensitivity (1/M dM/dV)	3.15 % / V
Temperature sensitivity (1/M dM/dT)	- 2.4 % / °C
Excess noise factor	2.1
Breakdown - operating voltage (V _b - V _r)	45 ± 5 V

They are received at PSI and undergo a set of tests in order to check their radiation hardness: they are irradiated with a Co-60 γ source to 5 kGy, at a dose rate of 2.5 kGy/hour. After 24 hours of relaxation time, breakdown voltage V_b and dark current I_{dark} at a gain of 50 are measured. They are sent to CERN, where the noise is measured and they are annealed in an oven for 4 weeks at $T=80^\circ\text{C}$. Then V_b and I_{dark} are re-measured to check for any changes. Potentially unreliable APDs are rejected if they show a significant shift of V_b after irradiation, high I_{dark} or noise (Figure 2)

The rejection rate is approximately 5%, the main reason being high noise after irradiation (3-3.5%), the other criteria accounting for less than 0.6% each.

The APD production is nearly finished:

- All ordered APDs (130 000) have been received
- ~ 20 000 APDs are still on the screening line
- 103 000 have already been sent to Lyon for capsule production
- The last APDs are foreseen to be sent by July 2004

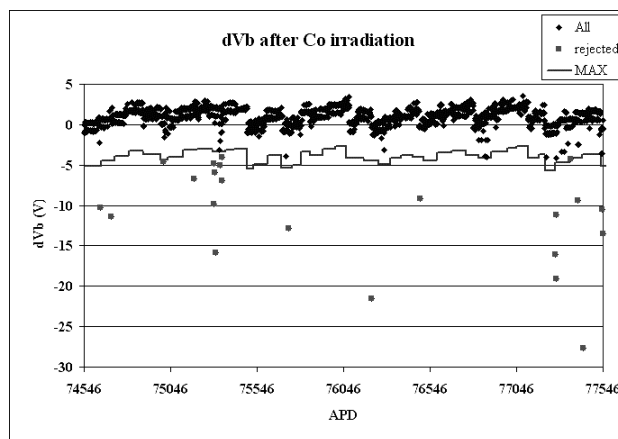


Figure 2: Rejection due to the shift of breakdown voltage as a function of APD serial number.

In Lyon, a pair of APDs is assembled in parallel and a kapton cable is soldered to form a capsule. On one of every 10, a temperature sensor with its own kapton cable is added. The following quality checks are performed: gain curve, I_{dark} , breakdown voltage noise and pulse shape are measured and the results are recorded in the CRISTAL database. The rejection rate (mainly due to high noise) is less than 1 %.

The capsules for 24 Super Modules have already been constructed and tested. It is foreseen to test the last capsule by June 2005.

3.3. “Bare” Super Module assembly

In the 2 regional centers (CERN and Rome), the capsules are glued on the crystals at a rate of 50 per day and Modules are assembled (400 or 500 crystals). Four Modules are then grouped together at CERN to form the bare Super Module. Up to now, 50 Modules (35%) and 10 Super Modules (28%) have been assembled.

4. The end caps

The crystals of the end caps are all identical, slightly shorter and wider than those of the barrel (3 x 3 x 22 cm³). Arrays of 5 x 5 crystals are grouped in identical modules called ‘Super Crystals’ which in turn make four identical ‘Dees’ with 3662 crystals each.

Due to the high radiation levels in the End cap region, APDs cannot be used. We use instead Vacuum Photo Triodes (VPT), which are in fact single-stage photomultipliers with a gain close to 10. They are manufactured by Research Institute Electron, St Petersburg, Russia. Out of total 15500, 7600 VPTs have been delivered.

5. The Preshower

In front of the end caps, a fine granularity preshower detector improves $\gamma - \pi^0$ rejection. It is a sampling calorimeter made of two lead absorbers (2 and 1 X_0 respectively), each followed by a layer of silicon microstrip detectors. The two layers of detectors have their strips orthogonal to each other. More than 2100 (out of a total of 5000) silicon sensors have been received from the four production centers (Russia, India, Taiwan and Greece)

6. The light monitoring

The optical transmission of PbWO₄ crystals is reduced by gamma irradiation doses through the formation of color centers. Saturation is reached after a small dose and partial damage recovery can be observed in a few hours. This loss in extracted light, which depends on the dose rate (~ 3 - 5 % for 0.15 Gy/h), must be monitored over the full ECAL with a light monitoring system.

To follow damage and recovery during LHC cycles, we will use two laser systems with four wavelengths: blue/green (440/495 nm) where the transmission damage is significant and red (700/800 nm) where there is very little damage in order to separate out other effects in the readout system. The light is injected to

each crystal using quartz fibres. Laser fluctuations are measured by very stable (0.1 %) reference silicon PN diodes from Hamamatsu.

7. The cooling system

To reach the targeted energy resolution, cooling is a key issue since both the light yield (LY) of the crystals and the APD gain M depend on the temperature ($dLY/dT = -1.9\% / ^\circ C$ and $1/M dM/dT = -2.4\% / ^\circ C$). This implies that the temperature of the calorimeter in the APD and crystal region must be maintained at $18 \pm 0.05\ ^\circ C$ while each electronics channel dissipates 2.5 W. To be able to achieve the required performance, heat must be removed directly from the chips and the heat flow to the APD and the crystal minimized.

The cooling circuit has two functions: to regulate the temperature in the crystal region with a precision ΔT of typically a few $1/100\ ^\circ C$ by flowing water with a very precise temperature and to remove the dissipated heat by creating a good thermal coupling between the electronics and the water. This is accomplished by maintaining the electronics components in contact through gap filler and gap pad with stainless steel pipes carrying the cooling water embedded in aluminium cooling bars. Figure 3 shows the results obtained in a beam test in 2002.

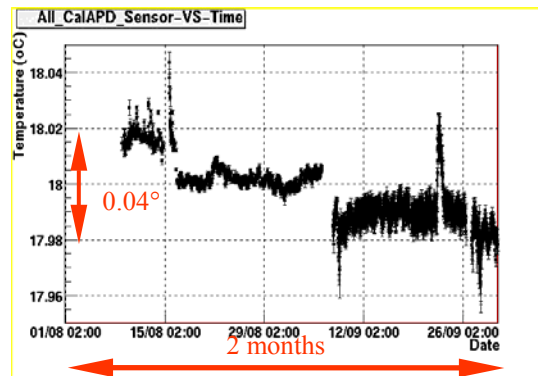


Figure 3: temperature stability obtained in 2002 beam test with a cooling system prototype on a module with 100 instrumented channels

8. The readout electronics

8.1. Introduction

In summer 2002 a new architecture was defined in order to reduce cost and facilitate the assembly of the readout electronics system:

- the trigger primitives are now computed on the detector
- the command and control signals are sent through a token ring identical to that of the CMS tracker
- the building block of the front end electronics consists of a trigger tower (TT) holding 25 channels and made of:
 - 1 motherboard
 - 1 low voltage (LV) regulator board
 - 5 very front end (VFE) boards (with 5 channels each)
 - 1 front end (FE) board
- only 2 optical fibers are used on each TT sending at 800 Mbits/s
 - the trigger primitives for every beam crossing (40 MHz)
 - the data on level 1 trigger request (around 100 kHz).

In 2003, the preamplifier and ADC combination was redesigned.

The previous design was based on analogue multiplexing with the FPPA (Floating Point Pre-Amplifier) which is a low noise preamplifier with 4 intermediate gain stages (33, 9, 5, 1) and analogue multiplexing of the highest non saturating signal. It used a commercially available ADC: AD9042 from Analog Devices. Slow-control measurements (temperature, leakage current) were available directly on-chip.

The new design uses digital multiplexing and consists of a MGPA (MultiGain Pre-Amplifier) with 3 gain stages (12,6,1) and 3 ADCs. The highest non-saturating signal is chosen after digitization. The slow control measurements are performed by a dedicated service chip (DCU). Both chips are produced in IBM 0.25 μm technology that permits lower cost and a faster turnaround.

This solution gives better performance but necessitates new chips to be developed.

8.2. *The new ASICs*

The first version of the MGPA has been tested in beam in summer 2003. No major problem was found.

A new ADC has been developed: ADC41240 (quad-12 bit ADC with on-board selection logic). Version 1 of these chips has been also used in test beams in 2003. A minor problem on Vref layout routings has been identified and version 2 chips were received in March. The tests performed on them show that this problem is cured.

The FENIX chips (situated on the FE board) have two main functions: to generate the Trigger Primitives (Trigger Tower transverse energy, bunch crossing assignment) and to read out the data when a positive trigger decision is received. There are 7 chips on each FE board, all of the same type but running in 3 different operation modes (Strip mode to receive the data from the VFES, TCP mode to generate the trigger primitives and DAQ to send the data).

Finally a new interface chip between the ADC and the FENIX (LVDS to LVCMOS level converter) had to be developed.

A number of chips, equivalent to that needed to equip at least 3 SMs, has been fabricated and will be ready by mid 2004. If they work as expected, all needed chips for the entire calorimeter will be sent to fabrication by the end of 2004.

8.3. *VFE boards*

All of the VFE boards will undergo three consecutive tests:

- Pre-production in the factory in order to validate the production and obtain a very high production yield (>99%).
- Burn-in to get rid of “infant mortality” of the weak components.
- Calibration, using a calibrated charge generator and a digital readout system.

The results from the measurements are stored in the construction Data Base.

9. Test beam results

9.1. *Precalibration*

Due to the delay in fabrication of the Super Modules and the fact that there will be no beam available at CERN in 2005, we will not be able to precalibrate all the SM in beam. Nevertheless, we have shown we can obtain a first

intercalibration from the data stored in the construction Data Base (the principal information is the light yield measured in the Regional Centers, corrected for capsule and electronics gains). This procedure has been checked (Figure 4) by comparing these results (Lab LY) with test beam ones (Test Beam LY):

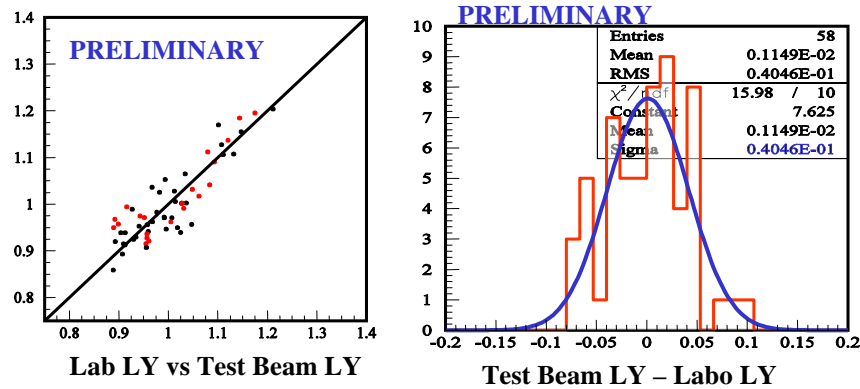


Figure 4 Comparison between the results measured during the detector construction and test beam

This comparison shows that intercalibration coefficients can be obtained from the construction data with a precision of $\sim 4\%$. Work is still going on in order to improve these results.

At the start of LHC operation, a fast intercalibration based on ϕ symmetry in minimum bias events will give a precision close to 2% in a few hours. With the electron pair invariant mass reconstruction of events coming from $Z \rightarrow e^+e^-$, it is possible to provide the intercalibration of calorimeter regions and to set the absolute energy scale. With the help of the tracker measurements, isolated electrons from $W \rightarrow ev$ will permit the target resolution of 0.5% to be reached.

9.2. Energy resolution

The data show low frequency noise, the result of which is a pulse baseline that varies from event to event. This effect is present in all channels with a uniform (15 - 20 %) spatial correlation. The baseline variation can be subtracted, event-by-event, by using an appropriate set of weights to compute the signal amplitude. After correction, the noise for the sum of nine crystals is 129 MeV, corresponding to a noise per channel of about 43 MeV.

Figure 5 shows the energy resolution for the sum of nine crystals. These results are obtained with events selected when the incoming electron is located in a $4 \times 4 \text{ mm}^2$ window at the center of the crystal. They confirm that the design performance can be reached.

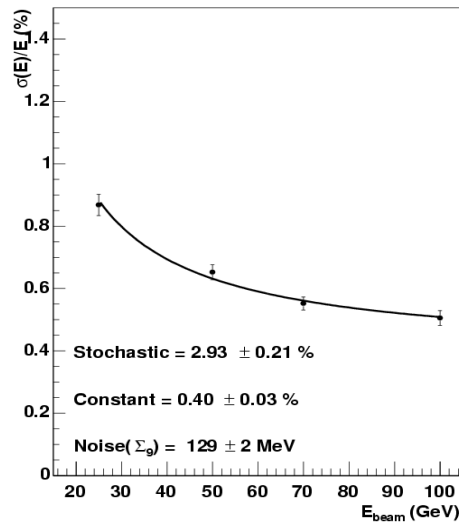


Figure 5: Energy resolution for the sum of nine crystals obtained at four different energies

10. Conclusions

The CMS electromagnetic calorimeter collaboration has already achieved encouraging results on crystal and photodetector quality control, electronics, monitoring and cooling systems, 2003 test beam results with new electronics. The detector construction now enters a new challenging phase:

- Production of the crystals
- Production and integration of the electronics
- Precalibration in the beam of as many Super Modules as possible

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