THE ELECTROMAGNETIC CALORIMETER OF THE CMS EXPERIMENT

Xth Vienna Conference on Instrumentation
19 – 24 February 2007, Vienna, Austria

M. Diemoz
On behalf of the CMS ECAL Group
Outline

• General considerations
• Crystals
• Photodetectors
• Readout
• Key points in energy resolution
• Recent results
• Status of the construction
Compact Muon Solenoid

Main CMS goal: search for Higgs and new physics

- Length ~ 22 m
- Diameter ~ 15 m
- Weight ~ 14500 t

For a light Higgs (as suggested by present data)

$$H \rightarrow \gamma \gamma$$

best channel. Narrow width, irreducible background:

**ECAL resolution crucial!**
ECAL layout

PWO: PbWO$_4$  
about 10 m$^3$, 90 t

Barrel: $|\eta| < 1.48$  
36 Super Modules  
61200 crystals (2x2x23cm$^3$)

EndCaps: $1.48 < |\eta| < 3.0$  
4 Dees  
14648 crystals (3x3x22cm$^3$)
Target CMS ECAL resolution: 0.5% at high energy (+ suitable 2 $\gamma$ angle resolution)

$\Rightarrow$ 120 GeV Higgs boson discovered at 5 $\sigma$

with $\leq$10 fb$^{-1}$ or 100 days @ low luminosity

$(10^{33} \text{ cm}^{-2}\text{s}^{-1})$

To comply with LHC and CMS conditions ECAL must be:

- fast
- compact
- highly segmented
- radiation resistant

$T$ dependent: -2%/°C

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation length cm</td>
<td>0.89</td>
</tr>
<tr>
<td>Moliere radius cm</td>
<td>2.2</td>
</tr>
<tr>
<td>Hardness Moh</td>
<td>4</td>
</tr>
<tr>
<td>Refractive index nm</td>
<td>2.3</td>
</tr>
<tr>
<td>Peak emission nm</td>
<td>420</td>
</tr>
<tr>
<td>% of light in 25 ns</td>
<td>80%</td>
</tr>
<tr>
<td>Light yield (23 cm) $\gamma$/MeV</td>
<td>100</td>
</tr>
</tbody>
</table>

Very low light output

Very effective in high energy $\gamma$ containment
PWO production

BARREL ingot

Crystal delivery:
critical path of ECAL construction

Two suppliers:
BTCP (Bogoroditsk, Russia)
SIC (Shanghai, China)

~ 99% of EB crystals delivered (61k)
EE crystals: 700 xl delivered (preseries)
Last Barrel crystal delivery: Feb 2007
Last Endcap crystal delivery: Feb 2008

Vienna 22-02-07
M. Diemoz - INFN Roma
PWO quality insurance

Automatic control of:
- Dimensions and shape
- Transmission (radiation hardness)
- Light yield and uniformity
PWO production quality

**Crystal Light Yield (Bogo)**
- Entries: 54899
- Mean: 10.26
- RMS: 1.251

**Front non Uniformity (Bogo)**
- Entries: 54899
- Mean: -0.1399
- RMS: 0.1673

**LY → stochastic term of energy resolution**

**FNUF → constant term of energy resolution**

**Crystal Light Yield vs SuperModule**

**Front non Uniformity vs SuperModule**

\[ \frac{d(LY)}{dX_o} \]
Light loss is characterised by an ‘induced absorption’

Under irradiation at room temperature, a dynamic equilibrium forms between formation and annealing of colour centres.

$\rightarrow$ Light loss saturates at a value that depends on dose-rate

CMS specification requires: $\mu_{420} < 1.5 \text{ m}^{-1}$
(Under uniform (lateral) $^{60}$Co irradiation at $>30 \text{ Gy/hr}$)

Under LHC-like conditions for the Barrel ($\sim 0.15 \text{ Gy/hr}$)
$\rightarrow$ Light yield loss $\leq 6\%$
Photodetectors for PWO

Barrel - Avalanche photodiodes (APD)
Two 5x5 mm² APDs/crystal
- Gain: 50    QE: ~75% @ \( \lambda_{\text{peak}} = 420 \text{ nm} \)
- Temperature dependence: -2.4%/°C
- Gain dependence on bias V: 3%/V
- Delivery complete

Endcaps: - Vacuum phototriodes (VPT)
More radiation resistant than Si diodes (with UV glass window)
- Active area ~ 280 mm²/crystal
- Gain 8 -10 (B=4T)    Q.E.~20% at 420 nm
- Delivery complete
On detector electronics

Energy → Light

Light → Current

Current → Voltage

Voltage → Bits

Bits → Light

Clock & Control

Trigger data

DAQ data

PbWO₄
Crystal

APD
VPT

Multi-Gain
(x 1, x 6, x 12)
Pre Amplifier

Multi-channel
12-bit ADC
40 MHz

Data pipeline
Trigger primitives

optical data link
driver
800 Mbit/s

100 m Fibers
to counting room

Front End card (FE)

Trigger Sums
Data

Trigger Tower (TT)
25 crystals

Very Front End card (VFE)

Data pipeline

Trigger primitives

optical data link
driver
800 Mbit/s

IBM CMOS 0.25 μm technology

Vienna 22-02-07
Off Detector electronics

- Barrel VME modules production completed:
  - DCC (data)
  - CCS (control)
  - TCC-68 (trigger)

- Endcap DCC and CCS available.
  - TCC-48 in prototyping phase.

First 4 VME crates 3x(TCC;CCS;DCC) tested and installed
Energy resolution

\[ \sigma(E) = \frac{a}{E} + \frac{b}{\sqrt{E}} + c \]

**Stochastic Term**
- Lateral Containment 5x5 (1.5%)
- Photo-statistics (2.3%)
- Preshower (5%)
- Total Barrel 2.7%
- Total Endcap 5.7%

**Noise Term**
- Barrel 155 MeV (210 HL)
- Endcap 770 MeV (915 HL)

**Constant Term**
- Leakage: front, rear, dead material < 0.2%
- CMS full shower simulation
  - LY Uniformity effect < 0.3%
  - Temperature stabilization < 0.2%
    - \( \Delta T < 0.05^\circ C; @ 18^\circ C \) over a time interval \( t \sim t_{\text{calibration}} \)
    - \( dLY/dT = -2.0\%/{^\circ C} \) @ 18°C;
    - \( d\text{Gain}_{\text{APD}}/dT \sim -2.4\%/{^\circ C} \)
  - APD bias stabilization < 0.2%
    - \( \Delta V < 66 \text{ mV} @ 380 \text{ V} \); over a time interval \( t \sim t_{\text{calibration}} \)
    - \( d\text{Gain}/dV = 3.1\%/{\text{V}} \)
  - Intercalibration by light injection monitor and physics signals
    - (most of the energy in a single crystal goal < 0.5% )
APD HV & Cooling systems

50% system installed USC55

Trigger tower integrated on the cooling bars

Electronics in contact with stainless steel pipes embedded in Al cooling bars.

Delivery complete

CAEN A1520E board

Lab qualification:
ΔV < 66 mV over 1 month at 380 V

Power to remove ~2.6 W/ch

bottom SM

0.1 °C

ΔT at APD when electronics is powered-up
At high energy the resolution is dominated by channel intercalibration

Interchannel response spread ~15% (mainly LY variation in PWO production)

Precalibration:
• LY lab measurements: 4.5%
• cosmics for all SM: <2%
• test beam for 10 SM: <0.5%  (POSTER A07 F. Ferri & P. Govoni)

In situ (MC detailed studies):
• $W \rightarrow e^+ e^- \nu \bar{\nu}$ intercalibration: 0.5% with 5 fb$^{-1}$ in the central region (ultimate single $x_l$ resolution, precision limited by statistics)
• $\pi^0 \rightarrow \gamma\gamma$ under study

Vienna 22-02-07  M. Diemoz - INFN Roma
ECAL monitoring system

Expected $\gamma$ dose-rate on crystals at LHC high luminosity:
$0.2-0.3$ Gy/h (EB) $\rightarrow$ $15$ Gy/h (EE)

During LHC cycles, a continuous variation of signal is expected

To follow and correct, a fiber-distributed Laser system monitors the light response of each crystal

Laser fluctuations measured by PN diodes. Stability $0.1\%$.

Simulation of signal evolution
$\eta=0.9$ - Low Lumi

test beam data

Vienna 22-02-07
M. Diemoz - INFN Roma
Pre-calibration with Cern-SPS high energy electron beams (from 15 GeV to 250 GeV) mandatory to understand the system

- 2004 Test-beam with 1 Super Module (45 days of data taking; detailed system test)
- 2006 Test-beam(s)
  - 10 SM calibrated (1 twice, 13600 x1)
  - Detailed studies E, $\eta$ behaviour
  - Combined test with HCAL (1SM)

Optimize the $\pi^0$ reconstruction/selection
Test beam

**Ferri&Govoni**

- **9 SM**
- **PRELIMINARY**

- calibrated S25 centre_Xtals
- **uncalibrated**

**REFERENCE FOR OTHER METHODS**

**LAB LY**

σ = 4.5%

- **8 SM**

**COSMICS**

σ = 1.9%

- **1 SM**

**PRELIMINARY**

- SM22 x 2
- Reproducibility of intercalibration

**Ferri&Govoni**

- **0.2 %**

**REFERENCE FOR OTHER METHODS**

- **Ferri&Govoni**

Entries 13110
Mean -0.7107E-02
RMS 0.4992E-01

χ²/ndf 154.0 / 48
Constant 688.0
Mean -0.9564E-02
Sigma 0.4459E-01

σ = 4.5%

- **8 SM**

**COSMICS**

σ = 1.9%

- **1 SM**

**PRELIMINARY**

- SM22 x 2
- Reproducibility of intercalibration

**Ferri&Govoni**

- **0.2 %**

**REFERENCE FOR OTHER METHODS**

- **Ferri&Govoni**
Resolution in 3x3 crystals

E (GeV)

2004 TB

\[ \frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} \oplus \frac{125}{E(\text{MeV})} \oplus 0.3\% \]

Preliminary results on 2006 TB data confirm this performance

Vienna 22-02-07 M. Diemoz - INFN Roma

Test Beam position (\(n\))
Test beam

Impact point correction based on energy deposits in the crystal cluster (should be usable for photons!)

Correct by a function of log ratios of energies in 3x3 matrix
- universal in $\eta$ (and $\phi$)
- energy independent

In the full crystal fiducial volume
the target high energy resolution 0.5% is reached
EB Construction

Assembly and test of modules in RC: END by March 2007
EB Construction

Cooling and electronics integration: completion by May 2007
EE Construction

EE crystal production started @ SIC (China) and pre-production @ BTCP (Russia)

- Mechanics for SC construction in hand
- VPT in hand
- 16 Super Crystals (5x5 xl) assembled & fully tested
- on detector electronics in production

Backplates successfully test mounted on HCAL

Preparing for Super Crystals assembly at full speed @ CERN
Magnet Test Cosmic Challenge

Toward CMS
(major exercise for muon system)

SPRING – SUMMER 2006

ECAL:
• Installation exercise
  • Check tools
  • Check sequence
  • Check services
• Check operations in 4T field
• DAQ integration in CMS
• DCS integration in CMS
• Data Quality Monitor test on a “system” of Super Modules
• 1 week of global data taking APD @ M=200 as in cosmics calibration
MTCC

EB installation device
Super Module

SM Rails on HB+

Insertion at point 5

HCAL
ECAL
SM5

Enfourneur

Vienna 22-02-07
M. Diemoz - INFN Roma
MTCC

Clearance between 2 SM: 6 mm

Services connected, ready for magnet and data taking tests of the experiment

Final installation in CMS foreseen in mid 2007 (Barrel) and 2008 (EndCaps + Preshower)
MTCC

TB results confirmed noise/ch ~ 40MeV

No B-induced changes in the pedestal RMS

ΔRMS pedestals 0T-3.8T 3400 ch
Conclusions

• Barrel crystal production is near to the end (beginning of March 2007), Endcaps one just started at SIC and being prepared at BTCP.
• All the other EB components and most of the EE ones have been delivered.
• A lot of care is being put in controlling and maintaining the quality in all the details during construction.
• Intercalibration: 100%@ 4-5% (LY), 90%@ 2% (cosm), 25% ~0.5%(TB e)
• Test-beam campaigns (25% Barrel) demonstrate that the actual ECAL meets the design performance.
• Integration in CMS tested with success during MTCC-2006
• ECAL Barrel will be inserted in CMS mid 2007, Endcaps and Pre-shower in 2008 in time for the Physics Run.
• Lots of exciting new physics can be investigated with CMS ECAL from the challenging H->\gamma\gamma channel to simpler high mass resonances (2008!)