Performance and physics goals

Paul Lecoq
CERN, Geneva
On behalf of the CMS-ECAL group

So funktioniert der Large Hadron Collider

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SCINT07 - Wake Forest, 04 - 08 June 2007

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Outline

- General considerations
- Crystals
- Photodetectors
- Readout
- Key points in energy resolution
- Recent results
- Status of the construction
Main CMS goal: search for Higgs and new physics

For a light Higgs (as suggested by present data) \( \mathcal{H} \rightarrow \gamma \gamma \) best channel. Narrow width, irreducible background: \textbf{ECAL resolution crucial!}
The Physics Reach of CMS

Higgs

Supersymmetry

Luminosity for 5σ discovery, fb⁻¹

M (TeV)

95% C.L. exclusion

5σ discovery

χ² production threshold

100 pb⁻¹

10 Luminosity/expt (fb⁻¹)

ATLAS + CMS
**Challenges & Choices**

**Challenges:**
- Fast response (25ns between bunch crossings)
- High radiation doses and neutron fluences
  (10 year doses: $10^{13}$ n/cm², 1kGy at $\eta=0$  $2\times10^{14}$ n/cm², 50kGy at $\eta=2.6$)
- Strong magnetic field (4 Tesla)
- On-detector signal processing
- $\pi^0/\gamma$ discrimination
- Long term reproducibility

**Choices:**
- Lead tungstate crystals
- Avalanche photodiodes (Barrel), Vacuum phototriodes (Endcaps)
- Electronics in 0.25 µm CMOS
- Pb/Si Preshower detector in Endcap region
- Laser light monitoring system
To comply with LHC and CMS conditions ECAL must be:

- fast
- compact
- highly segmented
- radiation resistant

Temperature dependence ~2%/°C
→ Stabilise to ≤ 0.1°C

Formation and decay of colour centres in dynamic equilibrium under irradiation
→ Precise light monitoring system

Low light yield (1.3% NaI)
→ Photodetectors with gain in mag field

### CMS requests and PWO

<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 @ 420nm</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) γ/MeV</td>
<td>100</td>
</tr>
</tbody>
</table>

Very low light output

Very effective in high energy γ containment

Temperature dependence: -2%/°C

T dependent: -2%/°C

CMS requests and PWO
ECAL layout

Barrel: \(|\eta| < 1.48\)
- 36 Super Modules
- 61200 crystals \((2\times2\times23\text{cm}^3)\)

EndCaps: \(1.48 < |\eta| < 3.0\)
- 4 Dees
- 14648 crystals \((3\times3\times22\text{cm}^3)\)

PWO: PbWO\(_4\)
- about 10 m\(^3\), 90 t
On optical quality & size

1995  1998

On radiation hardness

Front irradiation 0.15 Gy/h

Specification: -6%

Dose (Gy)

On production technology

BARREL ingot

On slow components

Decay analyse of green and blue components of PbWO$_4$ scintillation

On mechanical properties & processing

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Crystal production

- Barrel crystal production complete since Feb 2007
- Endcap crystal production has started at both producers
  - ~ 2500 crystals now available.
  - Quality of endcap crystals similar to those of barrel type from both sources
  - In-kind contribution of 1500 crystals from Russia agreed.
  - Contract for last 5500 crystals being finalized (end production February 2008)

Two suppliers:
- BTCP (Bogoroditsk, Russia)
- SIC (Shanghai, China)
PWO quality control

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

LY → stochastic term of energy resolution

FNUF → constant term of energy resolution

Crystal Light Yield (Bogo)

- Entries: 54899
- Mean: 10.26
- RMS: 1.251

Front non Uniformity (Bogo)

- Entries: 54899
- Mean: -0.1399
- RMS: 0.1573

Crystal Light Yield vs SuperModule

Front non Uniformity vs SuperModule

\[ \frac{\text{d}(\text{LY})}{\text{d}X_0} \]

\[ \gamma \]

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Crystal Radiation Resistance

Light loss is characterised by an ‘induced absorption’

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

→ Light loss saturates at a value that depends on dose-rate

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

Under LHC-like conditions for the Barrel (~0.15 Gy/hr)
→ Light yield loss $\leq 6\%$

$\mu(\lambda) = \frac{1}{L_{\text{xtl}}} \ln \left( \frac{T_0(\lambda)}{T_{\text{rad}}(\lambda)} \right)$

Verification:

BTCP: Use correlation between sharpness of absorption edge and radiation hardness (Check with sample irradiations)

SIC: All crystals irradiated by producer
Photodetectors for PWO

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

**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
- All delivered and tested

$d_{\text{eff}} \sim 6 \mu$m
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

40 ns shaping

25 ns sampling

Data pipeline

Trigger primitives

optical data link driver 800 Mbit/s

100 m Fibers to counting room

25 ns sampling
On detector electronics

Trigger Tower (TT)  
25 crystals

Very Front End card (VFE)

Front End card (FE)

Trigger Sums

Data

ASICs in 0.25 μm IBM CMOS Technology
Very high yield (typically >85%)

ADC
MGPA
FENIX

RMS: gain 12
Noise distribution for 1700 channels of SM13

30 MeV
45 MeV
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.

10/12 VME crates (TCC; CCS; DCC) tested and installed
Energy resolution

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

Stochastic Term
Main contribution from:
- Lateral Containment
- Photo-statistics
- Test beam measurement for Barrel 2.8%

Noise Term
- Test beam measurement for 3x3 matrices in Barrel 125 MeV

Constant Term 0.3% in test beam
- Leaks (front, rear, dead material)<0.2%
- Temperature effect < 0.3%
- Temperature drift: \( \Delta T < 0.05 ^\circ C \) over a time interval t\( t_{\text{calibration}} \)
- Gain of APD: \( \frac{\text{dGainAPD}}{\text{dT}} \sim -2.4 \% /^\circ C \)
- APD bias: \( \Delta V < 66 \text{ mV} @ 380 \text{ V} \) over a time interval t\( t_{\text{calibration}} \)
- Gain of 3x3: \( \frac{\text{dGain}}{\text{dV}} = 3.1 \% / V \)
- Intercalibration by light injection monitor and physics signals (most of the energy in a single crystal goal < 0.5%)

All parameters according to specifications set more than 10 years ago

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Trigger tower integrated on the cooling bars

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

Delivery complete

75% system installed USC55

CAEN A1520E board

Power to be removed ~2.6 W/ch
160kW for Barrel

Deliver complete

Lab qualification: \( \Delta V < 66 \text{ mV} \) over 1 month at 380 V

\( \Delta T \) at APD when electronics is powered-up

bottom SM

0.1 °C

Entries 1395

Mean 32.77

RMS 13.42

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Calibration

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%

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

laser correction
EB Modules Construction

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

Cooling and electronics integration: completed in May 2007
EE Construction

EE crystal production started
> 2500 crystals produced @ BTCP and SIC

- Mechanics for SC construction in hand
- VPT in hand
- 20 Super Crystals (5x5 x1) assembled & fully tested
- on detector electronics in production

Backplates successfully test mounted on HCAL

Super Crystals assembly @ CERN
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 xl)
  - Detailed studies $E$, $\eta$ behaviour
  - Combined test with HCAL (1SM)

Optimize the $\pi^0$ reconstruction/selection
Test Beam results

Resolution in 3x3 crystals
central e beam incidence

\[ \sigma(E) / E (\%) \]

CMS ECAL

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

Test beam electrons

4x4 mm\(^2\) region
“central incidence”

3 x 3 matrix around Crystal 184

3 x 3 matrix around Crystal 204

3 x 3 matrix around Crystal 224

Position (m)
Test beam results

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

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

Corrected energy (GeV)

![Graph showing corrected energy distribution](image)

![Graph showing impact point correction](image)

Number of events

Fit results:
$m = 120.0\text{ GeV}$
$\sigma = 0.60\text{ GeV}$
$\sigma / m = 0.50\%$
CMS installation
Conclusions

• Barrel crystal production is completed (61200 crystals, Feb 2007)
• Endcaps one (15478 crystals) just started at BTCP and SIC
• All other EB components and most of the EE ones have been delivered.
• Strict quality control procedures in all phases of construction.
• Intercalibration: 100%@ 4-5% (LY), 100%@ 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->γγ channel to simpler high mass resonances (2008!)
Spares
**Preshower detector**

Rapidity coverage: \(1.65 < |\eta| < 2.6\) (End caps)

Motivation: Improved \(\pi^0/\gamma\) discrimination

- 2 orthogonal planes of Si strip detectors behind 2 \(X_0\) and 1 \(X_0\) Pb respectively
- Strip pitch: 1.9 mm (63 mm long)
- Area: 16.5 m\(^2\) (4300 detectors, 1.4 \times 10^5 channels)

High radiation levels - Dose after 10 yrs:
- \(\sim 2 \times 10^{14} \text{n/cm}^2\)
- \(\sim 60 \text{kGy}\)

\(\Rightarrow\) Operate at \(-10^\circ\text{C}\)
Test beam

9 SM PRELIMINARY

uncalibrated

13110 -0.7107E-02 0.4992E-01

Constant 688.0 Mean -0.9564E-02 Sigma 0.4459E-01

σ = 4.5%

SM22 x 2 Reproducibility of intercalibration

COSMICS σ = 1.9%

REFERENCES FOR OTHER METHODS

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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

Insertion at point 5

EB installation device

Super Module

SM Rails on HB+

HCAL

Enfourneur

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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)
TB results confirmed noise/ch ~ 40MeV

No B-induced changes in the pedestal RMS

ΔRMS pedestals
0T-3.8T
3400 ch

B=0T rms g12 (1ADC=37MeV)

rms gain12 B=0T
Entries 3400
Mean 1.103
RMS 0.07752

Δ(rms) fed600 and fed 451
Entries 3400
Mean -0.004193
RMS 0.09079