Case study: The Lead Tungstate Calorimeter for CMS

(With acknowledgements to CMS colleagues, particularly R M Brown at RAL but all errors and omissions are the responsibility of Peter Hobson at Brunel!)

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The **Compact Muon Solenoid** Detector for LHC

**Physics goals:** SUSY, Higgs, Heavy flavours, heavy ions

- **Total mass:** 13,500t
- **Overall Diameter:** 15.0m
- **Overall Length:** 21.6m
- **Magnetic field:** 4T
High resolution electromagnetic calorimetry is a basic design objective of CMS.

Benchmark physics process:
Sensitivity to a low mass Higgs via $H \rightarrow \gamma \gamma$

$$\sigma_m/m = 0.5\left[\sigma_{E_1}/E_1 \oplus \sigma_{E_2}/E_2 \oplus \sigma_\theta/\tan(\theta/2)\right]$$

Where $\sigma_E/E = a/\sqrt{E} \oplus b \oplus c/E$

Aim: Barrel End cap

Stochastic term: $a = 2.7\% \quad 5.7\%$
(photoelectron statistics/shower fluctuations)

Constant term: $b = 0.55\% \quad 0.55\%$
(non-uniformities, shower leakage)

Noise term: Low $\mathcal{L} \quad c = 155\text{MeV} \quad 205\text{MeV}$

High $\mathcal{L} \quad 210\text{MeV} \quad 245\text{MeV}$

(Angular resolution limited by uncertainty in position of interaction vertex)
ECAL design choices

- ECAL (and HCAL) within magnetic vol
- Homogenous active medium (PbWO$_4$)
- Magnetic field-tolerant photodetectors with gain:
  - Avalanche photodiode (APD) for barrel
  - Vacuum phototriode (VPT) for end caps
- Pb/Si Preshower detector in end caps

Properties of dense inorganic scintillators

<table>
<thead>
<tr>
<th>Property</th>
<th>BGO</th>
<th>BaF$_2$</th>
<th>CeF$_3$</th>
<th>PbWO$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g/cm$^3$]</td>
<td>7.13</td>
<td>4.88</td>
<td>6.16</td>
<td>8.28</td>
</tr>
<tr>
<td>Rad length [cm]</td>
<td>1.12</td>
<td>2.06</td>
<td>1.68</td>
<td>0.89</td>
</tr>
<tr>
<td>Int length [cm]</td>
<td>21.8</td>
<td>29.9</td>
<td>26.2</td>
<td>22.4</td>
</tr>
<tr>
<td>Molière rad [cm]</td>
<td>2.33</td>
<td>3.39</td>
<td>2.63</td>
<td>2.19</td>
</tr>
<tr>
<td>Decay time [ns]</td>
<td>60</td>
<td>0.9</td>
<td>8</td>
<td>5(39%) 15(60%) 100(1%)</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>630</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Refractive index</td>
<td>2.15</td>
<td>1.49</td>
<td>1.62</td>
<td>2.30</td>
</tr>
<tr>
<td>Max emiss [nm]</td>
<td>480</td>
<td>210</td>
<td>300</td>
<td>420</td>
</tr>
<tr>
<td></td>
<td>310</td>
<td>340</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp coef [%/°C]</td>
<td>-1.6</td>
<td>0</td>
<td>0.14</td>
<td>-2</td>
</tr>
<tr>
<td></td>
<td>-2</td>
<td>-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rel light yield</td>
<td>18</td>
<td>4</td>
<td>8</td>
<td>1.3</td>
</tr>
</tbody>
</table>
### ECAL Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Barrel</th>
<th>End caps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coverage</td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>$\Delta \phi \times \Delta \eta$</td>
<td>$0.0175 \times 0.0175$</td>
<td>$0.0175 \times 0.0175$ to $0.05 \times 0.05$</td>
</tr>
<tr>
<td>Xtal size ($mm^3$)</td>
<td>$21.8 \times 21.8 \times 230$</td>
<td>$30.0 \times 30.0 \times 220$</td>
</tr>
<tr>
<td>Depth in $X_0$</td>
<td>25.8</td>
<td>24.7</td>
</tr>
<tr>
<td># of crystals</td>
<td>61200</td>
<td>14648</td>
</tr>
<tr>
<td>Volume ($m^3$)</td>
<td>8.14</td>
<td>2.7</td>
</tr>
<tr>
<td>Xtal mass (t)</td>
<td>67.4</td>
<td>22.0</td>
</tr>
</tbody>
</table>

3° off-pointing pseudo-projective geometry
**Radiation levels in ECAL**

**Absorbed dose after 10 years**

**Effect of radiation on PbWO$_4$ (after intense R&D)**
- No change in scintillation properties
- Small loss in transmission through formation of colour centres
- Damage saturates
- Slow self-annealing occurs
- Loss in light yield of a few percent corrected with monitoring system
- No damage observed with neutrons

BUT see later slides!
Photodetectors – solid state

• Silicon is the primary material since in general we are detecting fast scintillation or Cherenkov light (near UV to visible)
• Silicon diode technology is well advanced and the quantum efficiency (QE) is high (around 80% peak)
• Silicon devices are tolerant to quite high radiation levels, although there are problems with hadrons.
• Silicon photodiodes are linear over many orders of magnitude
• The *Avalance Photodiode* has internal gain of about 30 (optimum value).
• See
Avalanche photodiodes (APD)
- Operated at a gain of 50
- Active area of 2 x 25mm²/crystal
- Q.E. ~ 80% for PbWO₄ emission
- Excess noise factor is $F = 2.2$
- Insensitive to shower leakage particles ($d_{\text{eff}} \sim 6 \mu m$)
- Irradiation causes bulk leakage current to increase → electronic noise doubles after 10 yrs - acceptable
Hamamatsu type S8148
QE, Gain vs applied bias voltage,
Excess Noise Factor

Photodetectors – solid state

- Silicon is *not* cheaper per unit area than vacuum photodetectors (for areas greater than a few mm\(^2\))
- Really large devices cannot be made (200 mm\(^2\) is the upper limit)
- Problem of damage from high neutron flux in hadron collider experiments such as those at the LHC.
- Need low noise (= expensive) pre-amplifiers
- Hard to do *photon counting*. 
Photodetectors: end caps

Endcaps: Vacuum phototriodes (VPT)

Produced by RIE, St Petersburg, Russia
More radiation resistant than Si diodes (with UV glass window)
- Active area ~ 280 mm$^2$
- Gain ~10 (B=4T)  Q.E. ~ 20% (420 nm)
- Fast devices (simple planar structure)

Gain vs. Dynode Voltage:
- $V(A)=1000V$
- $V(A)=800V$

Diagram:
- SEMITRANSPARENT PHOTOCATHODE
- MESH ANODE
- $\phi = 26.5$ mm
- 40
- 4.5
- 2.5
VPT Characteristics

VPT angle (deg.) vs. Relative Anode Response

-90 -60 -30 0 30 60

Only 8% loss of transparency after 20 kGy (10 years)

Critical magnetic field and radiation tolerance tests are done in the UK
**Construction: barrel**

**Submodule:** 2x5 Xtals with APD and FE electronics in 200μm glass fibre alveola

**Module:** 10x4 or 10x5 submodules mounted on a ‘Grid’, inside a ‘basket’

**Supermodule:** 4 Modules (1700 Xtals)
Barrel = 36 Supermodules
The endcap is mechanically complex
Tight tolerance on dimensions, deflections and thermal management.
Construction: end caps

'Supercrystal': carbon-fibre alveola containing 5x5 tapered crystals + VPTs + HV filter
- 156 Supercrystals per Dee
- All crystals have identical dimensions
- All Supercrystals are identical (apart from inner and outer circumference)
Ongoing developments have progressively increased the boule diameter:
Two barrel crystals are now cut from a single boule in current production
Even larger boules have been grown which could provide four crystals per boule

Crystal lab at ICSTM has studied in detail the formation and annealing of colour centres

- Transmission loss due to irradiation at 15 Gy/h for 24 hours.
- Induced absorption fitted with Gaussians at 2.3 eV (540nm) and 3.1 eV (400nm).
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 (60 mm long)
- Area: 16.5 m$^2$
  (4300 detectors, $1.4 \times 10^5$ channels)

High radiation levels - Dose after 10 years:
- $\sim 2 \times 10^{14}$ n/cm$^2$
- $\sim 60$ kGy

$\rightarrow$ Operate at -10$^\circ$ C
\(\pi^0/\gamma\) Discrimination

(\(\gamma\)-jet) is potentially the most serious background to \(H \rightarrow \gamma \gamma\)

Track isolation cut reduces (\(\gamma\)-jet) to \(\approx 50\%\) of the intrinsic (\(\gamma\)-\(\gamma\)) background (\(p_T\) cut = 2GeV/c)

Use \(\pi^0/\gamma\) discrimination in the ECAL to gain an extra margin of safety

Barrel: Lateral shower shape in crystals (limited by crystal size at high \(E_{\pi^0}\))

End cap: Cluster separation in preshower (limited by shower fluctuations at 3\(X_0\))
Test beam: Energy Resolution

Barrel - 3x3 crystals

\[ \frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus \frac{140\text{ MeV}}{E} \oplus 0.4\% \]

No preshower detector

Crystal 2184
E = 180 GeV
\( \sigma/E = 0.51\% \)

Endcap - 3x3 crystals

\[ \frac{\sigma_E}{E} = \frac{4.1\%}{\sqrt{E}} \oplus \frac{140\text{ MeV}}{E} \oplus 0.25\% \]

Crystal 2070
E = 280 GeV
\( \sigma/E = 0.40\% \)

Barrel specifications:
\[ \frac{\sigma_E}{E} = \frac{2.7\%}{\sqrt{E}} \oplus \frac{155\text{ MeV}}{E} \oplus 0.55\% \]
Energy resolution with preshower

Energy resolution degraded by Pb absorber
- partially restored using Si p.h. information

Excellent agreement between MC and data
TDR performance achieved for $E > 80 \text{ GeV}$
($E_T > 30 \text{ GeV}$ - OK for $H \rightarrow \gamma\gamma$
(even though Pb 10% too thick in this test!)
Laser Monitoring System

DATA LINK

ADC & OPTO

PREAMP

APD

CRYSTAL (1700/SM)

LEVEL-1 FANOUT

LEVEL-2 FANOUT

SWITCH (select SM/2)

LASER

MEM

SERIALISER

ADC (x12)

CTRL

OPTO

PN

FE

DATA LINK

CMS-ECAL MONITORING SYSTEM

~1.3 TeV

440 nm/500 nm
1 mJ (2x10^{15} \gamma)

(200 Channels)

(200 Channels)
Laser Correction for Effect of Radiation Damage

Laser-Beam Correlation

Tower 19

Slope = 2.02

Relative Response vs Time

- Laser
- Electrons (laser corrected)
- Electrons (laser and temp corrected)

± 0.2 %
Readout architecture

On-detector *light-to-light* readout

- 40 MHz Clock
- 12 bit precision
- 4 different gains \( \rightarrow >17 \) bit dynamic range
Cosmic ray data

CRAFT: Cosmic Run At Four Tesla
- continuous running for several weeks to gain operational experience
- > 300 M cosmic events collected
- magnetic field operated at 3.8T
- most CMS subsystems participating

Minimum ionizing particles deposit 250 MeV in ECAL. Increase efficiency: signal/noise enhanced (x4) in EB to the value of 20, by increasing the gain of the APD.

From Biino at ICATPP11 2009
**PbWO$_4$ Stopping Power**

Validate ECAL calibration with muons: measure energy deposition vs muon momentum

- momentum $p$ measured in the CMS silicon tracker
- $dE$: energy from ECAL cluster
- $dx$: length traversed in ECAL crystals
- $dE/dx$ energy deposit matched to the track corrected for muon path length

Tracker momentum matches well with ECAL energy loss, energy scale is correct

From Biino at ICATPP11 2009
Data-taking with LHC beam.

- Wed, 10 Sept. 2008
  - “Splash” events observed when beam (450 GeV, $4 \times 10^9$ p) struck closed collimators 150m upstream of CMS
  - Halo muons observed once beam (uncaptured and captured) started passing through CMS

High energy deposit in the calorimeters, particles travelling horizontally useful to commission forward detectors

“Splash” Event

From Biino at ICATPP11 2009
Rapidity and azimuth distributions of the ECAL channel with the highest ET in minimum bias events at 7 TeV

- Variations as a function of η are due to the detector geometry; ECAL endcap data are prescaled by a factor six for presentation purposes

- Variations as a function of phi, accurately reproduced in MC, reflect modularity and the inhomogeneity of the energy-equivalent noise in ECAL
Neutral pions

$\pi^0 \rightarrow \gamma\gamma$ in 7 TeV data about 1461 thousands candidates for $\int L=0.43\text{nb}^{-1}$

$\pi^0 \rightarrow \gamma\gamma$ where one of the two photons is reconstructed as a conversion
The precision of channel inter-calibration, using energy deposits, as a function of pseudo-rapidity in the ECAL barrel and endcap detectors.
Relative response to laser light (440 nm) measured by the ECAL laser monitoring system, averaged over all crystals in bins of pseudorapidity, for the 2011 and 2012 data taking periods.
Correcting for the effects of radiation damage using the laser monitoring system. Barrel calorimeter shown here.
The corrections work

Instrumental resolution in barrel is 1 GeV at the Z peak

The plot shows the improvements in Z->ee energy scale and resolution that are obtained from applying energy scale corrections to account for the intrinsic spread in crystal and photo-detector response, and time-dependent corrections to compensate for crystal transparency loss.
Non-optimised data (shown at EPS conference) from early Run 2 data in 2015. MC number is normalised to data and calibration is based on an extrapolation from Run 1 constants.