Electromagnetic Calorimetry at LHC

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ATLAS and CMS ECAL

• Requirements

• Designs

• Constructions

• Test Beam Results

• Commissions
Status of the SM Higgs

- Electroweak fit (incl. quantum corrections) to \( m_H \) is sensitive to \( m_{\text{TOP}}(=172.7 \pm 2.9 \text{ GeV}) \)

- Best-fit value:
  \[ m_H = 89^{+42}_{-30} \text{ GeV} \]

- Direct search limit:
  \[ m_H > 114.4 \text{ GeV} \]

- 95\% CL upper limit:
  \[ m_H < 207 \text{ GeV} \]
Evidence of $M_H \sim 115$ GeV at LEP
$H \rightarrow \gamma \gamma$ Search Needs Precision ECAL

**Natural width (GeV)**

<table>
<thead>
<tr>
<th>Natural width (GeV)</th>
<th>Higgs Mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>0</td>
</tr>
<tr>
<td>0.004</td>
<td>50</td>
</tr>
<tr>
<td>1.4</td>
<td>100</td>
</tr>
<tr>
<td>30</td>
<td>200</td>
</tr>
<tr>
<td>250</td>
<td>400</td>
</tr>
<tr>
<td></td>
<td>800</td>
</tr>
</tbody>
</table>

**LEP**

**LHC**

- $H \rightarrow \gamma \gamma$
- $H \rightarrow ZZ^* \rightarrow 4$ leptons
- $H \rightarrow ZZ \rightarrow 4$ leptons
- $H \rightarrow WW$ or $ZZjj$

Narrow width and large background

\[\sigma m / m = 0.5 [\sigma E_1 / E_1 \oplus \sigma E_2 / E_2 \oplus \sigma \theta / \tan(\theta/2)],\]

where $\sigma E / E = a / \sqrt{E} \oplus b \oplus c/E$ and $E$ in GeV
Requirements to ECAL at LHC

- Fast response: 25 ns between LHC bunch crossing
- Large coverage: up to $|\eta| = 3$
  - Barrel: $|\eta| < 1.5$, Endcaps: $1.5 < |\eta| < 3$
- Energy Resolution: $\sigma_E / E = a / \sqrt{E} \oplus b \oplus c / E$
  - as small as possible stochastic term (a), constant term (b) and noise term (c)
- Photon Angular Resolution: $\delta \theta < 50 \text{ mrad} / \sqrt{E}$
  - LHC bunch length 7.5 cm $\rightarrow$ H vertex spread 5.3 cm
- Good particle ID: $\gamma$/jet, particularly $\pi^0/\gamma$ discrimination
  - Strips and shower shape analysis
- Large dynamic range: 5 orders of magnitude
- Radiation resistance: $10^{13}$ n/cm$^2$ and 100 krad @ $\eta=0$, $2 \times 10^{14}$ n/cm$^2$ and 5 Mrad @ $\eta=2.6$ in 10 years
## Parameters of ATLAS and CMS ECAL

<table>
<thead>
<tr>
<th></th>
<th>ATLAS Lead/L. Ar ECAL</th>
<th>CMS PWO Crystal ECAL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Barrel</strong></td>
<td><strong>Endcaps</strong></td>
<td><strong>Barrel</strong></td>
</tr>
<tr>
<td># of Channels</td>
<td>110,208</td>
<td>83,744</td>
</tr>
</tbody>
</table>

### Lateral Segmentation ($\Delta \eta \times \Delta \phi$)

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Presampler</td>
<td>0.025 x 0.1</td>
<td></td>
</tr>
<tr>
<td>Strip/Preshower</td>
<td>0.003 x 0.1</td>
<td>0.005 x 0.1</td>
</tr>
<tr>
<td>Main Body</td>
<td>0.025 x 0.025</td>
<td>0.0175 x 0.0175</td>
</tr>
<tr>
<td>Back</td>
<td>0.05 x 0.025</td>
<td></td>
</tr>
</tbody>
</table>

### Longitudinal Segmentation

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Presampler</td>
<td>10 mm L. Ar</td>
<td>2 x 2 mm L. Ar</td>
</tr>
<tr>
<td>Strip/Preshower</td>
<td>~4.3 $X_0$</td>
<td>~4 $X_0$</td>
</tr>
<tr>
<td>Main Body</td>
<td>~16 $X_0$</td>
<td>~20 $X_0$</td>
</tr>
<tr>
<td>Back</td>
<td>~2 $X_0$</td>
<td>~2 $X_0$</td>
</tr>
</tbody>
</table>

### Designed Energy Resolution

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stochastic:</strong> a</td>
<td>10%</td>
<td>10 - 12%</td>
<td>2.7%</td>
</tr>
<tr>
<td><strong>Constant:</strong> b</td>
<td>0.7%</td>
<td>0.7%</td>
<td>0.55%</td>
</tr>
<tr>
<td><strong>Noise:</strong> C</td>
<td>0.25 GeV</td>
<td>0.25 GeV</td>
<td>0.16 GeV</td>
</tr>
</tbody>
</table>
ATLAS L. Ar Accordion ECAL

Three Cryostats
EM Barrel: $|\eta| < 1.475$
EM Endcaps: $1.4 < |\eta| < 3.2$
~190K readout channels
ATLAS L. Ar Accordion Structure

- Accordion electrodes
- 1 cryostat with 2 half barrels in \( \eta \)
- 16 modules in \( \phi \)
  - 1 module covers \( \eta: 0 \) to \( 1.4, \phi: 0.4 \)

**Endcap Cryostat**

**Half Barrel Cryostat**

- ECAL
- Back
- Middle
- Front
Why L. Ar Accordion

• Fast readout achieved with dedicated electronics and inherent cabling
  • L. Ar as active material inherently linear
  • Hermetic coverage
  • Readout allows flexible longitudinal and lateral segmentations
• L. Ar is inherently radiation hard
• Challenges:
  ➢ Calibration to achieve linearity
  ➢ Readout noise with fast shaping
ATLAS L. Ar ECAL Barrel Module

32 modules produced and tested at cold between 2001-2003
Assembly/insertion in cryostat end 2003
ATLAS L. Ar ECAL Barrel

Feedthrough
Calorimeter
Presampler
Solenoid
Beam tests using a real detector module with the production version of the readout electronics have been carried out.

Preliminary data indicate the electronics system is working up to its design spec:

- For 20 GeV electrons, the data MC comparison shows a significance of 2.6%.
- For 180 GeV electrons, the data MC comparison shows a significance of ~1%.

\[
\begin{align*}
\chi^2 / \text{ndf} & : 7.237 / 4 \\
\text{Constant} & : 217.6 \pm 8.8 \\
\text{Mean} & : 18.08 \pm 0.03 \\
\text{Sigma} & : 0.4749 \pm 0.0200 \\
\end{align*}
\]
ATLAS L. Ar Test Beam Resolution

- 2002: study with production modules
- 2004: material study with 0 to 75 mm of Al in front of the calorimeter

⇒ If amount of material is corrected, resolution is identical
ATLAS L. Ar ECAL Calibration

\[ E_{\text{rec}}^{\text{Calo}} = a_{E,\eta} + b_{E,\eta} E_{PS}^{\text{Clus}} + c_{E,\eta} \sqrt{E_{PS}^{\text{Clus}} \cdot E_{1}^{\text{Clus}}} + d_{E,\eta} \sum_{i=1,3} E_{i}^{\text{Clus}} \]

**a**

Offset $a$ [GeV] vs $E_{\text{beam}}$ [GeV]

**b**

Slope $b$ vs $E_{\text{beam}}$ [GeV]

**c**

Slope $c$ vs $E_{\text{beam}}$ [GeV]

**d**

At $E = 100$ GeV:

\[ f_{\text{amp}} = 0.181 \]

Sampling fraction correction $d$ vs $E_{\text{beam}}$ [GeV]
0.1% linearity achieved
• 2002: setup, so beam energy under was under control @0.03%
• 2004: 0.5% due to beam energy error (1%)
• 2004: Extended the study with different amounts of material
ATLAS L. Ar ECAL Uniformity

<table>
<thead>
<tr>
<th>Module</th>
<th>P13</th>
<th>P15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global constant term</td>
<td>0.62%</td>
<td>0.56%</td>
</tr>
</tbody>
</table>
ATLAS L. Ar Response to Muons

- Noise goes like $\approx \Delta \eta \times \Delta \phi$,
- Signal goes like sampling depth $\Rightarrow$ Most favourable S/N : Middle layer

Muons at $6\sigma$ from noise

With 100 $\mu$/cell: check physics timing to 0.6 ns for Commissioning with cosmics

Energy (GeV)

Time resolution: 6.1 ns

Entries

Noise
$\sigma = 42.2 \pm 0.6$ MeV

$\sigma = 284.1 \pm 1.1$ MeV

TOF-TDC (ns)
ATLAS barrel calorimeter being moved to the IP, Nov. 2005
EM Barrel: Wheels Insertion P3

ATLAS endcap calorimeters installation, winter-spring 2006
ATLAS L. Ar ECAL Road Map

2005 2006 2007 2008

Combined test beam (1% of ATLAS)

Detector installation

Integration, from detector to off-line cosmic runs

Global cosmic run

First beams

All L. Ar ECAL cryostats in cavern. Barrel is cold. Readout will grow with more power supplies. Data taking with cosmic starts 7/06 (barrel) and 12/06 (endcaps).
CMS Detector

- ECAL
- Tracker
- HCAL
- 4T solenoid
- Iron yoke
- Muon chambers

Total weight: 12,500 t
Overall diameter: 15 m
Overall length: 21.6 m
Magnetic field: 4 T
CMS PWO Crystal ECAL

**Barrel:** 36 Supermodules (18 per half-barrel)
61200 Crystals (34 types) – total mass 67.4 t
Dimensions: ~ 25 x 25 x 230 mm³ (25.8 X⁰)
\[ \Delta \eta \times \Delta \phi = 0.0175 \times 0.0175 \]

**Endcaps:** 4 Dees (2 per endcap)
14648 Crystals (1 type) – total mass 22.9 t
Dimensions: ~ 30 x 30 x 220 mm³ (24.7 X⁰)
\[ \Delta \eta \times \Delta \phi = 0.0175 \times 0.0175 \leftrightarrow 0.05 \times 0.05 \]

**Pb/Si Preshowers:**
4 Dees (2/endcap)
4300 Si strips (~ 63 x 1.9 mm²)
Why PWO Crystals

- Excellent resolutions for energy, position and photon angle (with vertex) measurements
- High density allows a compact detector
- Simple building blocks allow easy mechanical assembly, hermetic coverage and fine transverse granularity
- Single segment allows straightforward energy and position reconstruction

- Challenges:
  - Radiation damage of scintillating crystals
  - Temperature stabilization to 0.1°C
## Mass Produced Crystals

<table>
<thead>
<tr>
<th>Crystal</th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
<th>CsI</th>
<th>BaF₂</th>
<th>BGO</th>
<th>PWO(Y)</th>
<th>LSO(Ce)</th>
<th>GSO(Ce)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density (g/cm³)</strong></td>
<td>3.67</td>
<td>4.51</td>
<td>4.51</td>
<td>4.89</td>
<td>7.13</td>
<td>8.3</td>
<td>7.40</td>
<td>6.71</td>
</tr>
<tr>
<td><strong>Melting Point (°C)</strong></td>
<td>651</td>
<td>621</td>
<td>621</td>
<td>1280</td>
<td>1050</td>
<td>1123</td>
<td>2050</td>
<td>1950</td>
</tr>
<tr>
<td><strong>Radiation Length (cm)</strong></td>
<td>2.59</td>
<td>1.86</td>
<td>1.86</td>
<td>2.03</td>
<td>1.12</td>
<td>0.89</td>
<td>1.14</td>
<td>1.38</td>
</tr>
<tr>
<td><strong>Molière Radius (cm)</strong></td>
<td>4.13</td>
<td>3.57</td>
<td>3.57</td>
<td>3.10</td>
<td>2.23</td>
<td>2.00</td>
<td>2.07</td>
<td>2.23</td>
</tr>
<tr>
<td><strong>Interaction Length (cm)</strong></td>
<td>42.9</td>
<td>39.3</td>
<td>39.3</td>
<td>30.7</td>
<td>22.8</td>
<td>20.7</td>
<td>20.9</td>
<td>22.2</td>
</tr>
<tr>
<td><strong>Refractive Index a</strong></td>
<td>1.85</td>
<td>1.79</td>
<td>1.95</td>
<td>1.50</td>
<td>2.15</td>
<td>2.20</td>
<td>1.82</td>
<td>1.85</td>
</tr>
<tr>
<td><strong>Hygroscopicity</strong></td>
<td>Yes</td>
<td>Slight</td>
<td>Slight</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td><strong>Luminescence b (nm)</strong> (at peak)</td>
<td>410</td>
<td>550</td>
<td>420</td>
<td>300</td>
<td>480</td>
<td>425</td>
<td>402</td>
<td>440</td>
</tr>
<tr>
<td><strong>Decay Time b (ns)</strong></td>
<td>230</td>
<td>1250</td>
<td>30</td>
<td>630</td>
<td>300</td>
<td>30</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td><strong>Light Yield b,c (%)</strong></td>
<td>100</td>
<td>165</td>
<td>3.6</td>
<td>36</td>
<td>21</td>
<td>0.29</td>
<td>83</td>
<td>30</td>
</tr>
<tr>
<td><strong>d(LY)/dT b (%)/°C</strong></td>
<td>-0.2</td>
<td>0.3</td>
<td>-1.3</td>
<td>-1.3</td>
<td>-0.9</td>
<td>-2.7</td>
<td>-0.2</td>
<td>-0.1</td>
</tr>
<tr>
<td><strong>Experiment</strong></td>
<td><strong>Crystal</strong></td>
<td><strong>Ball</strong></td>
<td><strong>CLEO</strong></td>
<td><strong>BaBar</strong></td>
<td><strong>BELLE</strong></td>
<td><strong>BES III</strong></td>
<td><strong>KTeV</strong></td>
<td><strong>TAPS (L') (GEM)</strong></td>
</tr>
</tbody>
</table>

*a. at peak of emission;  b. up/lower row: slow/fast component;  c. PMT QE taken out.*
PWO: Short Radiation Length

1.5 \( X_0 \) Samples:
- Hygroscopic Halides
- Non-hygroscopic

Full Size Crystals:
- \( BaBar \) CsI(Tl): 16 \( X_0 \)
- L3 BGO: 22 \( X_0 \)
- CMS PWO(Y): 26 \( X_0 \)
PWO: Fast Scintillation

Recorded with Agilent 6052A digital scope

Fast Scintillators

- CsI, $\tau = 30/6$ ns
- CeF$_3$, $\tau = 35$ ns
- PWO, $\tau = 30/10$ ns
- LSO, $\tau = 40$ ns
- LYSO, $\tau = 40$ ns

Slow Scintillators

- CsI(Tl), $\tau = 1250$ ns
- CsI(Na), $\tau = 630$ ns
- NaI(Tl), $\tau = 230$ ns
- BGO, $\tau = 300$ ns
- BaF$_2$, $\tau = 630/0.9$ ns
PWO: Low Light Output OK for LHC

Measured with a Philips XP2254B PMT (multi-alkali cathode)

**Fast Scintillators**

**Slow Scintillators**

\[ L.O = F + S \left( 1 - e^{-\frac{t}{\tau_s}} \right) \]

<table>
<thead>
<tr>
<th></th>
<th>F</th>
<th>S</th>
<th>$\tau_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSO</td>
<td>0</td>
<td>2210</td>
<td>42</td>
</tr>
<tr>
<td>LYSO</td>
<td>0</td>
<td>2150</td>
<td>44</td>
</tr>
<tr>
<td>CaF$_3$</td>
<td>0</td>
<td>208</td>
<td>33</td>
</tr>
<tr>
<td>CsI</td>
<td>30</td>
<td>101</td>
<td>30</td>
</tr>
<tr>
<td>1.9</td>
<td>7.3</td>
<td>31</td>
<td></td>
</tr>
</tbody>
</table>

\[ L.O = F + S \left( 1 - e^{-\frac{t}{\tau_s}} \right) \]

<table>
<thead>
<tr>
<th></th>
<th>F</th>
<th>S</th>
<th>$\tau_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaI(Tl)</td>
<td>0</td>
<td>2604</td>
<td>245</td>
</tr>
<tr>
<td>CsI(Na)</td>
<td>0</td>
<td>2274</td>
<td>693</td>
</tr>
<tr>
<td>CsI(Tl)</td>
<td>0</td>
<td>2093</td>
<td>1220</td>
</tr>
<tr>
<td>BaF$_2$</td>
<td>98</td>
<td>1051</td>
<td>655</td>
</tr>
<tr>
<td>BGO</td>
<td>0</td>
<td>350</td>
<td>302</td>
</tr>
</tbody>
</table>
Temperature Dependent Light Output

PWO light output has large temperature coefficient, requiring a temperature stabilized environment.

![Graph showing temperature dependent light output for various crystals]

- **NaI(Tl)**: T.C. = -0.2 ± 0.1 %/°C
- **CsI(Tl)**: T.C. = 0.3 ± 0.1 %/°C
- **CsI(Na)**: T.C. = 0.4 ± 0.1 %/°C
- **CsI**: T.C. = -1.3 ± 0.1 %/°C
- **BaF₂**: T.C. = -1.3 ± 0.1 %/°C
- **CeF₃**: T.C. = -0.1 ± 0.1 %/°C
- **LSO**: T.C. = -0.2 ± 0.1 %/°C
- **LYSO**: T.C. = -0.2 ± 0.1 %/°C
- **BGO**: T.C. = -0.9 ± 0.1 %/°C
- **PWO**: T.C. = -2.7 ± 0.1 %/°C

**Temperature (°C)**

**Normalized Light Output**
**PWO Crystal Production**

**Crystal delivery determines ECAL Critical Path**

Two Suppliers:
- BTCP (Bogoroditsk, Russia) ~ 1,160/month
- SIC (Shanghai, China) ~ 140/month

~ 85% of Barrel crystals already delivered (52k of 61k)

Preseries of Endcap crystals: 100 BTCP, 300 SIC

- Last Barrel crystal delivery Feb 2007, ready for 2007 pilot run
- Last Endcap crystal delivery Jan 2008, ready for 2008 physics run
Photodetectors

**Barrel - Avalanche photodiodes (APD)**
- Two Hamamatsu S8664-55 APDs/crystal
  - Gain: 50
  - QE for PWO: ~75%
  - Temperature dependence: -2.4%/°C
  - 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)
- QE for PWO: ~20%
- Delivery ~92%
On-detector Electronics

VFE architecture for single channel

Noise distribution for 1,700 channels (one SM) measured in cosmic tests

Entries 1700
Mean 1.074
RMS 0.07066

30 MeV
45 MeV
Cooling and Temperature Stabilization

- Power dissipation of Barrel on-detector electronics ~160 kW
- Combined temperature sensitivity of (crystal + APD):
  \[ \frac{dA}{dT}_{APD+LY} \approx -4\% / ^\circ C \]
- Stabilise temperature to better than ± 0.05 °C
- Chilled water at 50l/s

\[ \Delta T \text{ at APD when electronics is powered-up (Worst case: Bottom Supermodule)} \]

Water manifold and pipes on SM

Cooling bars in direct contact with electronic cards
Construction: Barrel

2 Regional Centres: CERN and Rome

Assembly status:
27/36 bare SMs assembled
21/36 SMs completed
Production rate 4/month

Sub-module: 10 crystals
Super-module: 1700 crystals
Module: 400/500 crystals
Bare SM
SM with cooling
Construction: Endcaps

**Supercrystal**: 25 crystals

**Dee (½ endcap)**: 3662 crystals

**Production status**
- All mechanical parts delivered
- Endcap crystal production starts in summer 2006

**Backplates successfully test mounted on HCAL**
Each SM operated with cosmic rays for ~1 week
→ Intercalibration: 1-3% (stat) depending on $\eta$

Mip deposits ~250MeV
(increase APD gain from 50 to 200)

Status: 15 SM calibrated by cosmic rays

Cosmic muons through full crystal

Event: 4161 Cry: 168
Two energy resolution curves are compared:

- Including cuts on electron position to select only electrons hitting crystal centre => central impact resolution
- Without any cuts, but including cluster corrections => uniform impact resolution
Test Beam Result: Energy Resolutions

Energy resolution: \( \sigma E/E = 2.9/\sqrt{E} \oplus 0.3 \oplus 0.125/E \)
Effects of Crystal Radiation Damage

- **Induced absorption caused by color center formation:**
  - reduces light attenuation length and thus light output, and maybe
  - degrades light response uniformity (LRU)

- **Induced phosphorescence:**
  - increases readout noise

- **Reduced scintillation light yield:**
  - reduces light output and degrades light response uniformity

<table>
<thead>
<tr>
<th>Item</th>
<th>CsI(Tl)</th>
<th>CsI</th>
<th>BaF₂</th>
<th>BGO</th>
<th>PbWO₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color Centers</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Fluorescence</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Scintillation</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Recover @RT</td>
<td>Slow</td>
<td>Slow</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Dose Rate Dependence</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Thermal Annealing</td>
<td>No/Yes</td>
<td>No/Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Optical Bleaching</td>
<td>No/Yes</td>
<td>No/Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
PWO: No Damage in Scintillation

No variation in emission and light response uniformity

Calorimeter resolution would not be damaged even with light output loss
PWO: Radiation Induced Absorption

Radiation induces absorption caused by color center formation

From top to bottom:
- 200°C annealing
- 15 rad/h (65 h)
- 100 rad/h (63 h)
- 400 rad/h (62 h)
- 9000 rad/h (10 h)
Light output variations can be corrected by transmittance variations

\[ \delta_{LO/LO} \text{ vs. } \delta_{LT/LT} @ 100 \text{ rad/h} \]

\[ \Delta LO/LO_0 = -0.00 + 3.31 \times (\Delta LT/LT_0) \]

Transmittance @ 440 nm (%)

Time (hours)

SIC-570

Dose rate: 100 rad/h

Normalized at average value

Light output variations can be corrected by transmittance variations.
PWO: Damage is Dose Rate Dependent

\[ dD = \sum_{i=1}^{n} \{ -a_i D_i dt + (D_i^{all} - D_i) b_i R dt \} \]

\[ D = \sum_{i=1}^{n} \{ \frac{b_i R D_i^{all}}{a_i + b_i R} [1 - e^{-(a_i + b_i R)t}] + D_i^0 e^{-(a_i + b_i R)t} \} \]

- \( D_i \): color center density in units of m\(^{-1}\);
- \( D_i^0 \): initial color center density;
- \( D_i^{all} \) is the total density of trap related to the color center in the crystal;
- \( a_i \): recovery constant in units of hr\(^{-1}\);
- \( b_i \): damage constant in units of kRad\(^{-1}\);
- \( R \): the radiation dose rate in units of kRad/hr.

\[ D_{eq} = \sum_{i=1}^{n} \frac{b_i R D_i^{all}}{a_i + b_i R} \]
Laser Light Monitoring System

Nd:YLF Pump

Tunable Ti:S

Fibers at front for barrel crystal

Fibers at back for endcap crystal
A factor of two better stability has been observed in a run of 10 days, using laser pulse timing as the feedback input, when YLF current increased by 0.5 A.
Laser Monitoring Performance

Typically ~0.1 %

long term stability

in real environment

Test Beam Data

Resolution before/after irradiations & monitor corrections

Transparency variation measured to < 0.15 %
**In situ Calibration Strategy**

- **Lab measurements**
  - Pre-calibration based on lab Data (~4%)
  - Cosmit test beam data (1-3%)

- **Pre-calibration**
  - Calibration of few SM with 50/120 GeV electrons in test beam

- **In-situ calibration**
  - Fast in-situ calibration based on the principle that mean energy deposited by jet triggers is independent of $\phi$ at fixed $\eta$ (after correction for Tracker material) (~2-3% in few hours)
  - $\phi$-ring inter-calibration with $Z \rightarrow e + e$ (~1% in 1 day)

- Calibration to < 0.5% with $W \rightarrow \nu + e$ and 5 fb$^{-1}$ @ $\eta = 0$
Level 1 trigger rate dominated by QCD giving dozens of $\pi^0$s/event

Useful $\pi^0 \rightarrow \gamma\gamma$ decays selected online giving $\sim 10^3$ Hz rate

$\sim 500 \pi^0$/crystal/day expected skimmed event format: $\sim 1$ MB/sec

Daily calibration runs would give a precision of $\sim 1\%$
ECAL Barrel SM Integration

After commissioning and cosmic data taking of first ~10 super-modules (17,000 channels): ~15 channels are not working, ~15 channels are noisy

July 21, 2006, status:
- 27 bare SM
- 21 SM fully assembled
- 15 SM went through cosmic test
- 2 SM inserted in HCAL for magnet test
Supermodule Installation at SX5

ECAL Barrel installation

Insertion at point 5

SM Rails on HB+

Gap HB+/HB- ~ 1mm

2 SMs inserted 27 April for magnet test
CMS PWO ECAL Commission

- 18 SMs (EB+) will be inserted into HB+ at SX5 (surface).
- Maximum SMs (EB-) will be inserted into HB- at SX5 by mid-Jan..
- Remaining SMs will be commissioned at UXC (underground).

- Endcap Assembly plan assumes last EE crystal delivered end Jan 08
- Aim is to have Endcaps installed for 2008 Physics Run
- All cables and services are already installed
- Goal: D1 Sept07, D2 Nov07, D3 Jan08, D4 Apr08
Summary

• LHC physics requires precision ECAL
• LHC environment presents unprecedented technical challenge
• Design of ATLAS and CMS ECAL represent state of art development in calorimetric technology
• Construction of LHC ECAL runs smoothly
• Test beam results of LHC ECAL satisfy their design goals
• Commission of LHC ECAL is well under way
• Looking forward to wonderful physics at LHC