CMS is one of the four detectors at the 14 TeV LHC.
Outline

• Generalities and motivations
• Physics benchmark
• ECAL construction
• Status of PWO crystal quality
• Key point for energy resolution: Light Monitoring
LHC Experimental Conditions

Machine Luminosity: $10^{34}$ cm$^{-2}$ s$^{-2}$

$\sigma_{\text{inel}} = 100$ mb $\rightarrow 10^9$ events/s

$\sigma_{\text{higgs}} = 1$ pb $\rightarrow 10^{-2}$ events/s

20 events/crossing $\rightarrow 1000$ tracks

1 crossing/25ns

Neutrons: $10^{17}$ n/cm$^2$

Gammas: $10^7$ Gy

Extreme conditions for detectors

- Granularity ($10^5 \div 10^7$ channels)
- Speed of response
- DAQ + trigger ($10^9 \rightarrow 10^2$ ev/s)
- High radiation resistance
The Calorimeter

- 36 SMs (1.7k ch) in barrel, 4 Dees (3.5k ch) in endcaps.
- 62k crystal in barrel, 14k crystal in two endcaps. (11 m³)
- 2 APD’s/crystal @barrel, 1 VPT/crystal @endcaps
- 1 monitoring fiber/crystal for in situ monitoring.
- Electronics: 0.25 μm ASIC.
Why Crystals?

- Excellent physics potential because of good energy resolution
- High detection efficiency for low energy $e/\gamma$
- Structural compactness:
  - simple building blocks allowing easy mechanical assembly
  - hermetic coverage
  - fine transverse granularity
- Tower structure facilitates reconstruction
  - straightforward cluster algorithms for energy and position
  - electron/photon identification
BaBar CsI(Tl) Resolution

Crystal Calorimetry at Low Energies

6580 CsI(Tl)

Good light yield of CsI(Tl) provides excellent energy resolution at B factory energies

Energy resolution

\[ \frac{\sigma_E}{E} = \frac{\sigma_1}{\sqrt{E}} \oplus \sigma_2 \]

\[ \sigma_1 = (2.30 \pm 0.03 \pm 0.3)\% \]

\[ \sigma_2 = (1.35 \pm 0.08 \pm 0.2)\% \]
L3 BGO Resolution
Crystal Calorimetry at High Energies

<table>
<thead>
<tr>
<th>Contribution</th>
<th>&quot;Radiative&quot;+Intrinsic</th>
<th>Temperature</th>
<th>Calibration</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel</td>
<td>0.8%</td>
<td>0.5%</td>
<td>0.5%</td>
<td>1.07%</td>
</tr>
<tr>
<td>Endcaps</td>
<td>0.6%</td>
<td>0.5%</td>
<td>0.4%</td>
<td>0.88%</td>
</tr>
</tbody>
</table>

Barrel
\[ \sigma = 1.06\% \]

Endcaps
\[ \sigma = 0.86\% \]

45.6 GeV < \( E_{\text{Beam}} \) < 94.3 GeV

Energy vs. BGO energy / Beam energy
KTeV CsI Position Resolution

Sub mm position resolution is achievable.
L3 BGO & CMS PWO: 0.3 mm at high energies.
Physics with Crystal ECAL

Charmonium System Observed Through Inclusive Photons

Crystal Ball

SUSY Breaking with Gravitino

\[ e^+e^- \rightarrow \tilde{G}\bar{\chi}_1^0 \rightarrow \tilde{G}\bar{G}\gamma \]

189 GeV ≤ \(\sqrt{s}\) ≤ 208 GeV

Data
- \(\nu\bar{\nu}\gamma(\gamma)
- other
- \(\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma\)

Preliminary
Physics with Crystal ECAL (Cont.)

The CDF event: \(2\, e + 2\, \gamma + E_T^{\text{miss}}\)

SM expectation (\(WW\gamma\gamma\)) \(\sim 10^{-6}\) (PR D59 1999)

Possible SUSY explanation

\[
\begin{align*}
q\bar{q} \rightarrow \tilde{\nu}^+\tilde{\nu}^- & \rightarrow ee\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow ee\gamma\gamma\tilde{G}\tilde{G}
\end{align*}
\]

L3 should be able to observe

\[
e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \gamma\gamma\tilde{G}\tilde{G}
\]

Another possible channel

\[
e^+e^- \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow \gamma\gamma\chi_1^0\chi_1^0
\]

---

![Graph showing event signatures and mass distributions](image)
LHC Physics Benchmark: Higgs Hunt

LEP observed an excess of events around 115 GeV

H → γγ signal in CMS ECAL @ design resolution
Why Lead Tungstate (PWO)?

- Fast scintillation
- Small $X_0$ and $R_m$
- Can be made radiation hard
- Relatively easy to grow
- Massive production capability

- Low light yield
- High refractive index
- LY dependance on $T$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation length</td>
<td>cm 0.89</td>
</tr>
<tr>
<td>Moliere radius</td>
<td>cm 2.2</td>
</tr>
<tr>
<td>Hardness</td>
<td>Moh 4</td>
</tr>
<tr>
<td>Refractive index</td>
<td>2.3</td>
</tr>
<tr>
<td>Peak emission</td>
<td>nm 440</td>
</tr>
<tr>
<td>% of light in 25 ns</td>
<td>80%</td>
</tr>
<tr>
<td>Light yield (23 cm)</td>
<td>$\gamma$/MeV 100</td>
</tr>
</tbody>
</table>
PWO Crystal is Compact

1.5 $X_0$ Cubic

Full Size Samples

*BaBar CsI(Tl)*: 16 $X_0$

*L3 BGO*: 22 $X_0$

*CMS PWO(Y)*: 25 $X_0$
PWO Scintillation is Fast

![Graphs showing pulse height and time for different materials: CeF$_3$, CsI, PbWO$_4$, BaF$_2$, BGO, CsI(Tl) with comparison to F + S (1 - e$^{-t/\tau_s}$)].

<table>
<thead>
<tr>
<th>Material</th>
<th>F</th>
<th>S</th>
<th>$\tau_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CsI(Tl)</td>
<td>0</td>
<td>2050</td>
<td>1280</td>
</tr>
<tr>
<td>BaF$_2$</td>
<td>116</td>
<td>950</td>
<td>724</td>
</tr>
<tr>
<td>BGO</td>
<td>0</td>
<td>402</td>
<td>286</td>
</tr>
<tr>
<td>CeF$_3$</td>
<td>0</td>
<td>381</td>
<td>43</td>
</tr>
<tr>
<td>CsI</td>
<td>100</td>
<td>253</td>
<td>31</td>
</tr>
<tr>
<td>PbWO$_4$</td>
<td>11</td>
<td>17</td>
<td>35</td>
</tr>
</tbody>
</table>
Comparison: Crystals for HEP

<table>
<thead>
<tr>
<th>Crystal</th>
<th>NaI(Tl)</th>
<th>CsI(Tl)</th>
<th>CsI</th>
<th>BaF$_2$</th>
<th>BGO</th>
<th>PbWO$_4$</th>
<th>LSO(Ce)</th>
<th>GSO(Ce)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm$^3$)</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>Melting Point (ºC)</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>Radiation Length (cm)</td>
<td>2.59</td>
<td>1.85</td>
<td>1.85</td>
<td>2.06</td>
<td>1.12</td>
<td>0.9</td>
<td>1.14</td>
<td>1.37</td>
</tr>
<tr>
<td>Molière Radius (cm)</td>
<td>4.8</td>
<td>3.5</td>
<td>3.5</td>
<td>3.4</td>
<td>2.3</td>
<td>2.0</td>
<td>2.3</td>
<td>2.37</td>
</tr>
<tr>
<td>Interaction Length (cm)</td>
<td>41.4</td>
<td>37.0</td>
<td>37.0</td>
<td>29.9</td>
<td>21.8</td>
<td>18</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>Refractive Index $^a$</td>
<td>1.85</td>
<td>1.79</td>
<td>1.95</td>
<td>1.50</td>
<td>2.15</td>
<td>2.2</td>
<td>1.82</td>
<td>1.85</td>
</tr>
<tr>
<td>Hygroscopicity</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>Luminescence $^b$ (nm)</td>
<td>410</td>
<td>560</td>
<td>420</td>
<td>300</td>
<td>480</td>
<td>560</td>
<td>420</td>
<td>420</td>
</tr>
<tr>
<td>(at peak)</td>
<td>310</td>
<td>220</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decay Time $^b$ (ns)</td>
<td>230</td>
<td>1300</td>
<td>35</td>
<td>630</td>
<td>300</td>
<td>50</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>6</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light Yield $^{b,c}$ (%)</td>
<td>100</td>
<td>45</td>
<td>5.6</td>
<td>21</td>
<td>9</td>
<td>0.1</td>
<td>75</td>
<td>30</td>
</tr>
<tr>
<td>2.3</td>
<td>2.7</td>
<td></td>
<td></td>
<td></td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d(LY)/dT $^b$ (%/ ºC)</td>
<td>~0</td>
<td>0.3</td>
<td>-0.6</td>
<td>-2</td>
<td>-1.6</td>
<td>-1.9</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>~0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experiment</td>
<td>Crystal Ball</td>
<td>CLEO</td>
<td>BaBar</td>
<td>BELLE</td>
<td>KTeV</td>
<td>TAPS (L*) (GEM)</td>
<td>L3</td>
<td>BELLE</td>
</tr>
</tbody>
</table>

$^a$ at peak of emission; $^b$ up/low row: slow/fast component; $^c$ measured by PMT of bi-alkali cathode.
PWO Crystals Growth
BTCP: Czochralski  SIC: Modified Bridgman
Yttrium Distribution in Crystal

- The Glow Discharge Mass Spectroscopy (GDMS) was used to determine yttrium concentration in PWO crystals.

- A fit to the GDMS data extracts the yttrium segregation coefficient in PWO
  \[ K_e = 0.91 \pm 0.04 \]
PWO Crystal Quality Control

25 K crystals delivered

Automatic control of:
- Dimensions
- Transmission
- Light yield and uniformity

INFN/ENEA, Rome

CERN/lab27
Avalanche Photo Diode (APD)

Delivery, test and screening are completed

QC: $^{60}$Co to 5 kGy in 2 h; 80°C aging one month

2 APDs per crystal: 50 mm$^2$ active area
ECAL Module Assembly

Submodule: 10 crystals
Supermodule: 1,700 crystals
Module: 4(5)00 crystals
SM Construction

Modules assembled in Rome and CERN centers

About 40 modules (10 SM) are completed
CMS PWO ECAL Resolution

Radiation Damage?

Designed Resolution

Beam Test
Randomly Selected PWO Samples

BTCP: 20 from 1\textsuperscript{st} batch (100) for CMS endcaps
SIC: 20 from production batch for PrimEx

BTCP: 28.5\textsuperscript{2} x 220 x 30.0\textsuperscript{2} mm
SIC: 22\textsuperscript{2} x 230 x 22\textsuperscript{2} mm
Experiment

- All crystals went through (1) thermal annealing at 200°C, (2) irradiations by γ-ray at 15, 400 and 9k rad/h until equilibrium and (3) recovery.
- Properties measured: Transmittance, emission and excitation spectrum, light output, decay kinetics and light response uniformity, as well as their degradation, radiation induced color center and emission weighted radiation induced absorption coefficients.
- Light output degradation was only measured at 15 rad/h because of limited light output: less than 8 p.e./MeV for BTCP samples.
Thermal Annealing

• Rigorous temperature control both in amplitude and slope:
  - From RT to 200°C: 200 minutes;
  - Maintain at 200°C: 240 minutes;
  - From 200°C to 25°C: 400 minutes.

• Crystals are kept in dark at RT (18°C) after annealing. The minimum time between annealing and the 1st measurement is 48 hours.
Transmittance and Birefringence

*a axis*: better L.T., but non-isotropic transverse T. Both approaching theoretical limit

**BTCP**: grown along the *a axis*  

**SIC**: grown along the *c axis*

---

**BTCP-1971**

- 200°C annealing 4 hour
- Transverse (x)
- Transverse (y)
- Longitudinal (z)

**SIC-U517 (21.6 cm)**

- 200°C annealing 4 hour
- Transverse (x)
- Transverse (y)
- Longitudinal (z)

---

Calculated longitudinal T of CMS PWO crystal

- /\*c axis,
- \perp c axis, unpolarized light
- \perp c axis, e-polarized light
Light Output and Decay Kinetics

Both are fast, SIC samples have more light
### Comparison of L.T. and Light Yield

<table>
<thead>
<tr>
<th>Vendor</th>
<th>ILT@440 nm (%)</th>
<th>ILO (p.e./MeV)</th>
<th>50 ns/1 us</th>
<th>100 ns/1 us</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTCP</td>
<td>69.8 (1.4%)</td>
<td>6.4 (12%)</td>
<td>81.8 (4.0%)</td>
<td>95.8 (1.6%)</td>
</tr>
<tr>
<td>SIC</td>
<td>65.6 (1.5%)</td>
<td>10.1 (9.6%)</td>
<td>83.9 (4.1%)</td>
<td>95.9 (1.9%)</td>
</tr>
</tbody>
</table>

#### Initial L.T. @ 440 nm (%)

**BTCP-PWO**
- Mean: 69.83
- RMS: 0.9844

**SIC-PWO**
- Mean: 65.55
- RMS: 1.023

#### Light Output (p.e./MeV)

**BTCP-PWO**
- Mean: 6.393
- RMS: 0.7807

**SIC-PWO**
- Mean: 10.13
- RMS: 0.9760
Caltech $\gamma$-ray Irradiation Facilities

Open 50 curie Co-60: 15, 100 and 400 rad/h

Closed 2,000 curie Cs-137: 9k rad/h at center, up to 36k rad/h
Photoluminescence

No variation in either excitation or emission spectrum

No damage in scintillation mechanism
No Variation in Light Response Uniformity

The response \( y \) along the axis was fit to a linear function

\[
\frac{y}{y_{mid}} = 1 + \delta \left( \frac{x}{x_{mid}} - 1 \right)
\]

---

**Graphs**

**SIC-S412**

- 0 rad/h, \( \delta = (-1.1 \pm 0.6)\% \)
- 15 rad/h, \( \delta = (-1.1 \pm 0.6)\% \)
- 100 rad/h, \( \delta = (-2.4 \pm 0.6)\% \)
- 500 rad/h, \( \delta = (-0.8 \pm 0.6)\% \)
- 1000 rad/h, \( \delta = (-1.1 \pm 0.6)\% \)

**BTCP-2133**

- 0 rad/h, \( \delta = (-3.0 \pm 0.6)\% \)
- 15 rad/h, \( \delta = (-1.1 \pm 0.7)\% \)
- 100 rad/h, \( \delta = (-0.9 \pm 0.7)\% \)
- 500 rad/h, \( \delta = (-1.4 \pm 0.7)\% \)
- 1000 rad/h, \( \delta = (-1.8 \pm 0.7)\% \)
Light Output Degradation

5-15% and 15-30% light output loss under 15 and 500 rad/h
Damage is dose rate dependent
Damage in Longitudinal Transmittance

Radiation induced absorption caused by CC formation

**BTCP-2466**

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)
- 35000 rad/h (6.5 h)

**SIC-T5**

From top to bottom:
- 200°C annealing
- 15 rad/h (108 h)
- 400 rad/h (72 h)
- 9000 rad/h (24 h)
Comparison of Radiation Damage

SIC samples seem more radiation hard
Comparison of Transmittance Loss

SIC samples less diverse: Bridgman technology
One BTCP sample shows LT increase under irradiation

BTCP Samples

SIC Samples
Type III Sample: Transmittance Loss

Type III sample: preexisting intrinsic color center at 420 nm after 200 degree annealing, causing difficulty for monitoring with 440 nm light.
Investigation on BTCP Samples (I)

Three samples cut to 5 pieces: 4.3 cm each:
Type I: 2467, Type II: 2436, Type III: 2465
Investigation on BTCP Samples (II)

Anomaly is shown also at the Tail end (E and D)

Normalized Light output under certain dose rate in equilibrium for 4.2 cm long small pieces.

Normalized L.O. versus irradiation time under 15 rad/h for 4.2 cm long small pieces.
Investigation on SIC Samples (I)

Two anomalous samples were cut to pieces

Crystal ID: NO.4-1-20
Dopant: Y/150 at ppm

Seed 1 2  A  B  C  D  E  F  G  H  I  J 3 4

The length of seed is 20.0 mm, thickness of 1, 2, 3, 4 is 5.0 mm.
Dimension of AB, CD, EF, GH and IJ is: 25.0 x 25.0 x 44.3 mm³

Crystal ID: B13
Dopant: Y/150 at ppm

Seed Side B13a B13b

Dimension of B13a: 22.0 x 22.0 x 177.0 x 25.0 x 25.0 mm³
Dimension of B13b: 22.0 x 22.0 x 50.0 x 23.0 x 23.0 mm³
Investigation on SIC Samples (II)

Anomaly was found at the tail end: impurity related?

- AB: $L_Y \text{ As-received} = 17.9 \, \text{p.e./MeV}$, 1.8 rad/h
- CD: $L_Y \text{ As-received} = 17.9 \, \text{p.e./MeV}$, 1.8 rad/h
- EF: $L_Y \text{ As-received} = 16.7 \, \text{p.e./MeV}$, 1.8 rad/h
- GH: $L_Y \text{ As-received} = 15.7 \, \text{p.e./MeV}$, 1.8 rad/h
- IJ: $L_Y \text{ As-received} = 12.9 \, \text{p.e./MeV}$, 1.8 rad/h

**B13b**
- After 50°C, 4h annealing
- Dose rate: 4.0 rad/h

**B13a**
- After 50°C, 4h annealing
- Dose rate: 4.0 rad/h
Trace Analysis on SIC Samples

**GDMS on SIC PWO(Y) Samples (ppmw)**

by Shiva Technology West (November, 1999)

<table>
<thead>
<tr>
<th>Element</th>
<th>Seed/Tail 1</th>
<th>Seed/Tail 2</th>
<th>Seed/Tail 3</th>
<th>Seed/Middle/Tail 4</th>
<th>Tail 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>0.2/0.8</td>
<td>0.2/2.3</td>
<td>0.4/0.8</td>
<td>0.2/0.8/1.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Si</td>
<td>0.5/0.2</td>
<td>0.7/1.3</td>
<td>0.5/1.2</td>
<td>0.5/0.4/0.1</td>
<td>0.05</td>
</tr>
<tr>
<td>K</td>
<td>0.3/1.8</td>
<td>0.4/2.9</td>
<td>0.7/1.2</td>
<td>0.5/0.9/2.0</td>
<td>1.3</td>
</tr>
<tr>
<td>Ca</td>
<td>0.9/&lt;0.05</td>
<td>0.6/0.08</td>
<td>0.12/0.15</td>
<td>0.8/0.6/0.2</td>
<td>0.15</td>
</tr>
<tr>
<td>Cu</td>
<td>0.04/0.2</td>
<td>0.04/0.4</td>
<td>0.3/0.35</td>
<td>0.08/0.1/0.54</td>
<td>0.23</td>
</tr>
<tr>
<td>As</td>
<td>0.15/0.35</td>
<td>0.1/0.6</td>
<td>0.5/0.5</td>
<td>0.14/0.16/0.6</td>
<td>0.54</td>
</tr>
<tr>
<td>Y</td>
<td>40/45</td>
<td>40/50</td>
<td>30/35</td>
<td>40/40/60</td>
<td>50</td>
</tr>
<tr>
<td>Nb</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Mo</td>
<td>0.3/0.55</td>
<td>0.3/0.9</td>
<td>0.6/0.8</td>
<td>0.2/0.5/0.8</td>
<td>1.0</td>
</tr>
<tr>
<td>Sb</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Ba</td>
<td>0.1/0.1</td>
<td>0.1/0.1</td>
<td>&lt;0.05/0.06</td>
<td>0.3/0.15/0.07</td>
<td>0.1</td>
</tr>
<tr>
<td>La</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Eu</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>TC†</td>
<td>3.8/2.1</td>
<td>4.9/4.6</td>
<td>4.4/3.4</td>
<td>5.3/4.0/2.5</td>
<td>4.3</td>
</tr>
</tbody>
</table>

†: Total contamination, excluding Y.

Impurity segregation:
- Na, K, Cu, As, Mo: <1;
- Ca, Ba: >1;
- Y: slightly less, but close to 1.

SIC samples are doped with Y only.

---

April 20, 2004
Informal HEP Seminar at Caltech by Ren-yuan Zhu
## Trace Analysis on BTCP Samples

### GDMS on BTCP PWO(Y/Nb/La) Samples (ppmw)

by Shiva Technology (November, 2003)

<table>
<thead>
<tr>
<th>Element</th>
<th>2467 Seed/Tail</th>
<th>2436 Seed/Tail</th>
<th>2465 Seed/Middle/Tail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>0.95/0.98</td>
<td>2.5/5.2</td>
<td>3.8/3.4/5.2</td>
</tr>
<tr>
<td>Si</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>K</td>
<td>0.36/0.58</td>
<td>0.45/0.90</td>
<td>0.71/0.56/1.6</td>
</tr>
<tr>
<td>Ca</td>
<td>2.4/1.8</td>
<td>1.3/0.9</td>
<td>1.7/1.3/1.2</td>
</tr>
<tr>
<td>Cu</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>As</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Y</td>
<td>71/74</td>
<td>94/120</td>
<td>98/83/100</td>
</tr>
<tr>
<td>Nb</td>
<td>0.06/0.11</td>
<td>0.07/&lt;0.05</td>
<td>&lt;0.05/0.27/0.26</td>
</tr>
<tr>
<td>Mo</td>
<td>0.2/0.23</td>
<td>0.33/0.38</td>
<td>0.37/0.37/0.41</td>
</tr>
<tr>
<td>Sb</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Ba</td>
<td>1.7/1.5</td>
<td>1.5/1.2</td>
<td>5.3/1.7/2.5</td>
</tr>
<tr>
<td>La</td>
<td>250/140</td>
<td>200/130</td>
<td>280/160/150</td>
</tr>
<tr>
<td>Eu</td>
<td>0.6/0.5</td>
<td>0.8/1.4</td>
<td>1.1/0.53/0.3</td>
</tr>
<tr>
<td>TC†</td>
<td>6.4/5.7</td>
<td>7.0/10</td>
<td>13/7.9/11</td>
</tr>
</tbody>
</table>

†: Total contamination, excluding Y, Nb and La.

Impurity segregation:

- Na, K, Nb, Mo: <1;
- Ca, Ba, La: >1;
- Y: slightly less, but close to 1.

BTCP PWO is triple doped with Y/Nb/La!!!
Light Output & La Concentration

- The anti-correlation between the light output of PWO and its La concentration, may explain the low light yield of BTCP PWO.

- Further study is under way to clarify this issue.
RIAC or radiation induced color center density can be calculated precisely by using longitudinal transmittance (0.2%)

$$RIAC \text{ or } D_{\text{Color-Center}} = \frac{1}{LAL};$$

$$LAL = \frac{\ell}{\ln \left\{ \frac{T(1-T_s)^2}{\sqrt{4T_s^4 + T^2(1-T_s^2)^2 - 2T_s^2}} \right\}}$$

where $T$ is transmittance measured along crystal length $\ell$ and $T_s$ is the theoretical transmittance without internal absorption:

$$T_s = (1 - R)^2 + R^2(1 - R)^2 + \ldots = (1 - R)/(1 + R), \text{ with}$$

$$R = \frac{(n_{\text{crystal}} - n_{\text{air}})^2}{(n_{\text{crystal}} + n_{\text{air}})^2}.$$
Emission Weighted RIAC

$$\text{EWRIAC} = \frac{\int Riac(\lambda)Em(\lambda)d\lambda}{\int Em(\lambda)d\lambda}$$

a good measure of rad. damage
EWRIAC (1/m) and Normalized r.m.s.

<table>
<thead>
<tr>
<th>Vendor</th>
<th>15 rad/h</th>
<th>400 rad/h</th>
<th>9,000 rad/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTCP</td>
<td>0.16 (45%)</td>
<td>0.69 (37%)</td>
<td>1.43 (50%)</td>
</tr>
<tr>
<td>SIC</td>
<td>0.10 (33%)</td>
<td>0.51 (32%)</td>
<td>1.16 (48%)</td>
</tr>
</tbody>
</table>

**BTCP-PWO**

**SIC-PWO**

Emission weighted RIAC. (m⁻¹)

Dose rate (rad/h)
L. T. Loss versus Initial L.T. @ 360 nm

No correlation
EWRIAC versus Initial L.T. @ 440 nm

No correlation
Recovery Speed and Time Constant

Recovery at 18°C in 160 days: two time constants
Short recovery: BTCP: 36.0 h (27%), SIC: 43.6 h (33%)
Light Monitoring System

Initial calibration on test beam (as much crystals as possible)

Physics calibration *in situ*: $e^+e^-$ pair (resonance) and $e$ (E/p)

Monitoring crystal evolution by light injection system

Four wavelengths from laser to be distributed to 80 super-modules, then to 77k PWO.

- 440 nm
- 495 nm
- 709 nm
- 796 nm
LHC Beam Structure

Continuous monitoring during data taking

LHC = 88.924 μs

Beam gaps:

τ_1 = 3 lost bunches (rise kicker extr. PS = 85 ns)
τ_2 = 8 missing bunches (rise kicker inj. SPS = 220 ns)
τ_3 = 38 missing bunches (rise kicker inj. LHC = 0.94 μs)
τ_4 = 127 missing bunches (rise kicker extr. LHC = 3.17 μs)

Rate limited by DAQ at 100 Hz
Monitoring Wavelength Determination

\[ \Delta(T) \text{ versus } \Delta(LY) \]

\[ \text{Sensitivity and Linearity} \]

\[ \text{→ 440 nm is chosen for the best linearity} \]
Lasers at CERN for PWO Monitoring

The 1st laser system was installed in 2001, and used in 2002 beam test.

Ti:Sapphire Laser with Two Wavelengths

Nd:YLF Pump

Tunable Ti:S
Low Level Light Distribution

Long Term Stability: 0.1%

Monitoring
Low Level Fiber Distribution
Experiences in 2002 Beam Test
PWO Resolution With Light Monitoring


Before/after beam irradiation: 10% variation in light output
Summary (I)

- In the last seven years, CMS has taken a challenging project to build a precision crystal calorimeter at LHC.
- High quality PWO crystals and APDs are in mass production and detector construction is well under way.
- Radiation damage in PWO crystals is well understood. Variations of PWO crystal light output are monitored by a light monitoring system *in situ*.
- Important development has been achieved for precision crystal calorimetry in radiation environment. Looking forward to precision e/γ physics at LHC.
Summary (II)

- PWO samples from both BTCP and SIC have very good transmittance and fast light output. SIC samples produce 58% more light, which may be explained by 130-280 ppmw La doping in BTCP samples.

- Preexisting CC, causing light output increase under irradiation, is caused by contamination of mono-valent impurities.

- No correlations between radiation hardness and initial longitudinal transmittance was observed.

- Requiring degraded LAL>1 m, current mass-produced PWO crystals are radiation hard enough for environment of up to a few hundreds rad/h --- a great achievement for HEP and MS.