The Electromagnetic Calorimeter of the CMS Experiment

One of the four detectors at the 14 TeV LHC

Main goal: Higgs, SUSY

8th Topical Seminar on Innovative Particle and Radiation Detectors - Siena 22/10/2002
Outline

- General considerations and motivations
- Physics benchmark
- Crystals
- Photodetectors
- Readout
- Key points in energy resolution
- Regional Centers for assembly and test
LHC experimental conditions

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

\[ \sigma_{\text{inel}} = 100 \text{ mb} \rightarrow 10^9 \text{ events/s} \]
\[ \sigma_{\text{higgs}} = 1 \text{ pb} \rightarrow 10^{-2} \text{ events/s} \]

20 events/crossing $\rightarrow$ 1000 tracks

1 crossing/25ns

Neutrons: $10^{17}$ n/cm$^2$
Gammas: $10^7$ Gy

in 10 years

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
CMS ECAL Structure

≈75000 PWO Crystals + Preshower (Endcaps)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Barrel</th>
<th>Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta ) coverage</td>
<td>(</td>
<td>\eta</td>
</tr>
<tr>
<td>Granularity (( \Delta \eta \times \Delta \phi ))</td>
<td>0.0175 \times 0.0175</td>
<td>varies in ( \eta )</td>
</tr>
<tr>
<td>Crystal Dims. (cm(^3))</td>
<td>2.18 \times 2.18 \times 23</td>
<td>2.85 \times 2.85 \times 22</td>
</tr>
<tr>
<td>Depth in ( X_0 )</td>
<td>25.8</td>
<td>24.7 (+3( X_0 ))</td>
</tr>
<tr>
<td>No. of crystals</td>
<td>61,200</td>
<td>14,950</td>
</tr>
<tr>
<td>Crystal Volume (m(^3))</td>
<td>8.14</td>
<td>3.04</td>
</tr>
<tr>
<td>Photodetector</td>
<td>APDs</td>
<td>VPTs</td>
</tr>
<tr>
<td>Modularity</td>
<td>36 supermodules</td>
<td>4 Dees</td>
</tr>
</tbody>
</table>

Siena 22/10/2002

M. Diemoz – INFN Roma
Motivations for Crystals

- Excellent energy resolution (over a wide range)
- High detection efficiency for low energy e and γ
- Structural compactness:
  - simple building blocks allowing easy mechanical assembly
  - hermetic coverage
  - fine transverse granularity
- Tower structure facilitates event reconstruction
  - straightforward cluster algorithms for energy and position
  - electron/photon identification
Precision has a price... a long list to take care:

- Longitudinal and lateral shower containment
- Light production and collection
- Light collection uniformity
- Nuclear counter effect (leakage of particles in PD)
- Photo Detector gain (if any) stability
- Channel to channel intercalibration
- Electronic noise
- Dead material (energy loss and γ conversions)
- Temperature stability and uniformity
- Radiation damage
- Pileup
A question of philosophy...

A crystal calorimeter is a very precise instrument that requires a tremendous effort to be finalized

- understand & optimize crystal parameters
- technology for growing crystals
- ..... 
- extreme resolution very fragile

Is it worth?

If you look for some specific reaction...
Higgs hunt: low mass?

**Natural width (GeV)**

- 0.001
- 0.004
- 1.4
- 30
- 250

**Higgs Mass (GeV)**

- 0
- 50
- 100
- 200
- 400
- 800

**LEP**

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

**LHC**

**Evidence of $H \rightarrow \gamma\gamma$ signal**

**LEP observed an excess of events around 115 GeV**

**ECAL CMS @ design resolution**
Low mass Higgs discovery:

\[ \Gamma_H \ (m_H \approx 100 \text{ GeV}) \sim 2 - 100 \text{ MeV} \quad \Rightarrow \quad \Gamma_H / m_H \leq 10^{-3} \]

Precision given by experimental resolution

\[ m_{\gamma\gamma} = 2 \ E_1 \ E_2 \ (1 - \cos\theta) \]

\[
\frac{\sigma_m}{m} = \frac{1}{2} \left[ \left( \frac{\sigma_1}{E_1} \right)^2 + \left( \frac{\sigma_2}{E_2} \right)^2 + \left( \frac{\sigma_\theta}{\tan\theta / 2} \right)^2 \right]^{1/2}
\]

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

Target → 

\[ a \sim 0.025 \text{ GeV}^{1/2} \]
\[ b < 200 \text{ MeV} \]
\[ c \sim 0.005 \]

and an angular resolution

\[ \sigma_\theta \sim 50 \text{ mrad/}\sqrt{E} \]
L3 photon measurements

Beautiful instrument & excellent physics results

\[ \pi \text{ mass reconstruction} \Rightarrow \text{single gamma} \]
\[ \text{neutrino counting} \]

\[ N_\nu = 2.98 \pm 0.07 \pm 0.07 \]

most accurate model independent measurement
### Which crystal?

<table>
<thead>
<tr>
<th></th>
<th>NaI(Tl)</th>
<th>BaF2</th>
<th>CsI(Tl)</th>
<th>CsI</th>
<th>CeF3</th>
<th>BGO</th>
<th>PWO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho$</td>
<td>3.67</td>
<td>4.88</td>
<td>4.53</td>
<td>4.53</td>
<td>6.16</td>
<td>7.13</td>
<td>8.26</td>
</tr>
<tr>
<td>$X_0$</td>
<td>2.59</td>
<td>2.05</td>
<td>1.85</td>
<td>1.85</td>
<td>1.68</td>
<td>1.12</td>
<td>0.89</td>
</tr>
<tr>
<td>RM</td>
<td>4.5</td>
<td>3.4</td>
<td>3.8</td>
<td>3.8</td>
<td>2.6</td>
<td>2.4</td>
<td>2.2</td>
</tr>
<tr>
<td>$\tau$</td>
<td>250</td>
<td>0.8/620</td>
<td>1000</td>
<td>20</td>
<td>30</td>
<td>300</td>
<td>15</td>
</tr>
<tr>
<td>$\lambda_p$</td>
<td>410</td>
<td>220/310</td>
<td>565</td>
<td>310</td>
<td>310/340</td>
<td>480</td>
<td>420</td>
</tr>
<tr>
<td>$n(\lambda_p)$</td>
<td>1.85</td>
<td>1.56</td>
<td>1.80</td>
<td>1.80</td>
<td>1.68</td>
<td>2.15</td>
<td>2.29</td>
</tr>
<tr>
<td>LY</td>
<td>100%</td>
<td>15%</td>
<td>85%</td>
<td>7%</td>
<td>5%</td>
<td>10%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

**Typical light yield of NaI ~ 40000 $\gamma$/MeV**
The choice of Lead Tungstate

- Fast scintillation
- Small $X_0$ and $R_m$
- Intrinsic radiation hardness
- Relatively easy to grow
- Massive production capability

- Low Light Yield
- High index of refraction
- Strong LY dependance on $T$
Main CMS ECAL challenges

- Improve the low level of light yield of crystals
- Keep fast response (understand decay kinetics)
- Insure radiation resistance
- Improve growing and production techniques
- Achieve longitudinal response uniformity
- Develop solid state photodetector with gain (APD)
- Develop suitable radiation hard electronics
- Control effects below few permill
- Design low-Z support structure
- Test and assembly ~ 75000 crystals
Crystals R&D 1995 - 1998

Almost final barrel crystals

Theoretical transmission from Fresnel losses

Emission spectra

Photoluminescence decay

Siena 22/10/2002

M. Diemoz – INFN Roma
Facts on Radiation Damage

Total dose after 10 years of running (5x10^5 pb^-1)

- Only e.m. radiation produces a damage
- Scintillation mechanism is not affected
- Only crystal transparency is reduced
  - creation of color centers
- Damage level depends on dose rate
  - creation and annealing of color centers at room temperature
- Damage level reaches an equilibrium after a small administered dose
- Partial damage recovery in few hours
- Loss in extracted light of few % is tolerable and can be followed with a monitor system

Dose rates [Gy/h] in ECAL at luminosity L=10^{34} cm^{-2}s^{-1}

M. Diemoz – INFN Roma
\( \gamma \) induced radiation damage

Can be quantified by:

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

\[ \text{LY}_{\text{loss}} = \frac{\text{LY}_{\text{rad}}}{\text{LY}_0} \]

Absorption can be monitored through light injection.

Band edge slope correlated to radiation hardness!!
Siena 22/10/2002 M. Diemoz – INFN Roma

Crystals Preproduction


6000 crystals produced by BTCP

- Production yield
- Crystals quality
- Production rate
- Stability of parameters

Goals successfully achieved!
Preproduction Goals

- **Graph 1:**
  - Plotting Longitudinal Transmission (%) vs. Wavelength (nm)
  - Key data points:
    - 6000 crystals
    - 55% Transmission at 420nm

- **Graph 2:**
  - Bar charts showing Transmission at 420nm (%)
  - Data for batches 1, 8, and 14
    - Batch 1: Mean 61.88%, StDev 7.5%
    - Batch 8: Mean 69.01%, StDev 1.59%
    - Batch 14: Mean 70.97%, StDev 1.46%
Preproduction Goals

Front irrad., 1.5Gy, 0.15Gy/h

Statistics on 368 crystals
Mean: 2.45 %
StDev: 1.06%

Rejected for LT slope < 1.5%/m
Rejected for LT @350nm < 10%

N = 32 Xtabl
StDev: 1.21%
Mean: 3.39%

N = 33 Xtabl
StDev: 0.9%
Mean: 1.92%

N = 19 Xtabl
StDev: 1.21%
Mean: 0.92%

batch 1
batch 8
batch 14
2001: Crystals New Technology

Technology steps in Bogoroditsk

Barrel
- 32 mm
- 1996

Endcap
- 44 mm
- 1999

Barrel
- 65 mm
- End 2000

Significantly increase the production capacity: add flexibility to the production scenario
Production of barrel crystals started in 2001: 5700 crystals delivered
In parallel R&D to increase productivity (driven by endcap ingot success)
New Technology: Quality

**COMPARE:**
- 260 barrel xl produced with the standard technology
- 40 barrel xl produced with the new technology

**LY@8X0**
- N = 300 crystals
- Mean: 9.1 pe/MeV
- StDev: 0.57 pe/MeV

**LT@420**
- N = 300 crystals
- Mean: 69.91%
- StDev: 0.85%

**LT slope@inflection**
- N = 300 crystals
- Mean: 3.30%/nm
- StDev: 0.06%/nm

Siena 22/10/2002

M. Diemoz – INFN Roma
New Technology: Production

- 138 ovens upgraded for up to 85mm

- New cutting technology: yield!
Crystals New Technology

Technology for 65mm ingots under control: quality comparable with “standard crystals”

Further increase of the PWO ingot diameter under study: 2Endcap or 4Barrel crystals in one ingot is feasible
## Crystal production schedule

### Years 2001 - 2005

<table>
<thead>
<tr>
<th>Quarters</th>
<th>1Q</th>
<th>2Q</th>
<th>3Q</th>
<th>4Q</th>
<th>1Q</th>
<th>2Q</th>
<th>3Q</th>
<th>4Q</th>
<th>1Q</th>
<th>2Q</th>
<th>3Q</th>
<th>4Q</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EndCap crystals production in Russia</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Potential EE production</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Barrel Total</strong></td>
<td>7500</td>
<td>8000</td>
<td>8500</td>
<td>8700</td>
<td>8900</td>
<td>11.7K</td>
<td>14.7K</td>
<td>19.8K</td>
<td>26.4K</td>
<td>33.0K</td>
<td>39.6K</td>
<td>46.2K</td>
</tr>
<tr>
<td><strong>Cumulative</strong></td>
<td>200</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>1200</td>
<td>1450</td>
<td>7000</td>
<td>3550</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### CERN/ISTC #354b- 6000 barrel
- **Delivered**: 6000

### CERN/ISTC #1718- 30000 barrel
- **Schedule Sept 2001**: 1500, 1200, 2100, 2500, 2600, 1800, 2600, 2900, 2900, 2900, 2900, 1200
- **New sched**: 1500, 500, 500, 200, 200, 200, 400, 2500, 4000, 4000, 4000, 4000, 3200, 800
- **Delivered**: 1500, 500, 500, 200, 200, 200

### CERN/ETHZ Contract 26000 barrel
- **Contract SCIONIX**: 2600, 2600, 2600, 2600, 2600, 2600, 2600, 2600, 2600, 2600, 2600, 2600
- **Delivered**: 2600

### Additional order for Barrel (37th SM + spares)
- **Potential product**: 2150

---

Siena 22/10/2002

Assumes 2 crystals per ingot for barrel and endcap

M. Diemoz – INFN Roma
Avalanche Photo Diodes - Barrel

- Insensitive to B-field (4T)
- Internal gain (needed for PWO, $M=50$ used, $V_{M50} \approx 380V$)
- Good match to PWO scintillation spectrum (Q.E. $\approx 80\%$)
Critical points

- Contributions to all $\sigma(E)/E$ terms
  - $C$ & $I_{dark}$ $\Rightarrow$ $b$ $(1/E)$
  - Excess noise factor $\Rightarrow$ $a$ $(1/\sqrt{E})$
  - Gain stability $\Rightarrow$ $c$

- Nuclear counter effect
- Radiation hardness

APDs optimized with an extensive R&D program are now in production

- Capacitance 75 pF & $I_{dark}$ few nA
- $F=2.2$ (fluctuations in multiplication)
- $dM/dV = 3\%/V$ and $dM/dT = -2.3\%/oC$

$\Rightarrow b = 150 \text{ MeV} (\Sigma 5 \times 5 \tau_s = 40\text{ns})$
$\Rightarrow a$ increase $1.6\% \rightarrow 2.3\%$
$\Rightarrow c \sim 0.5\%$ develop very stable systems

$d_{eff} \equiv 6 \mu m$ (accept able response to ionizing radiation)

Idark increases with neutron irradiation:
$\sqrt{2}$ contribution to noise of single channel after 10 years running

2 APDs per crystal: 50 mm$^2$ active area

Siena 22/10/2002

M. Diemoz – INFN Roma
Vacuum Phototriodes - Endcaps

Vacuum Phototriode (VPT):
Single stage PM tube with fine metal grid anode

- B-field orientation favourable for VPTs (Axes: $8.5^\circ < |\theta| < 25.5^\circ$ wrt to field)
- More radiation hard than Si diodes (with UV glass window)
- Gain 8 -10 at $B = 4$ T
- Active area of $\sim 280$ mm$^2$/crystal
- Q.E. $\sim 20\%$ at 420 nm
On-detector Light-to-Light readout

- 40 MHz clock
- High dynamic range to measure an energy interval 50 MeV → 2 TeV

**ALL RADIATION HARD**

A difficult and costly project!
Major revision of the project imposed by budget and possible thanks to 0.25µm CMOS rad hard technology:

- $\Sigma$ trigger e data storage on detector
- read out of data only if L1 OK
- three links each trigger tower (25 x1)

- Reduction of about a factor 8 in the number of data links
- Simplification of off-detector electronics
- Equivalent performances
New construction scheme

Bare/Dressed Super Modules

SM's installation

- Bare SMs
- Stuffed SMs

EB+ ready to install
EB- ready
EB+
EB-
Design Resolution is achievable

280 GeV electrons:
• no sign of rear leakage, which could cause direct signal in APD

Resolution as a function of energy:
• on 1999 prototype, matrix with 30 preproduction crystals and APDs

\[
\sigma = \frac{2.74\%}{E} \oplus 0.40\% \oplus \frac{142\text{MeV}}{E}
\]
Energy resolution

Standard parametrization:

- **a**: stochastic term from Poisson-like fluctuations
  - sampling contribution
    - (natural advantage of homogeneous calorimeters)
  - intrinsic contribution from photostatistics \( \Rightarrow \) L.Y.
  - other contributions often important
- **b**: noise contribution, relevant at low energy
  - electronic noise converted in energy units through \( N_{pe}/\text{MeV} \) \( \Rightarrow \) 
    - \( b \) depends on Light Yield too
- **c**: constant contribution, dominated by stability
  - dangerous limitation to high energy resolution
  - important contribution from calibration constants

\[
\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c
\]
Resolution: stochastic term $a$

- **Photostatistics contribution**, including:
  - $L_Y$
  - Light collection efficiency
  - Geometrical efficiency of the photodetector
  - Photocathode quantum efficiency

  \[ \frac{N_{pe}}{GeV} = 4000 \text{ for } 0.5 \text{ cm}^2 \text{ APD} \rightarrow 1.6\% \]

- Electron current multiplication in APD, contributing a square root of excess noise factor, $F = 2$

  \[ 1.6 \times 1.4 = 2.25\% \]

- Lateral containment ($5 \times 5$ matrix)

  \[ \rightarrow 1.5\% \]

**Total stochastic term**

\[ a = 2.7\% \]
40 ns shaping time, summed over 5x5 channels

- Serial noise (p.d. capacitance) $\propto 1/\sqrt{t}$
  - 150 MeV
- Parallel noise (dark current) $\propto \sqrt{t}$, mostly radiation induced
  - negligible at the start of the experiment
  - 30 MeV after one year at low luminosity
  - 100 MeV after one year at high luminosity
- Physics pile-up (simulated, with big uncertainties)
  - low luminosity 30 MeV
  - high luminosity 100 MeV

Total contribution
- low luminosity 155 MeV
- high luminosity 210 MeV
Resolution: constant term $c$

- leakage (front, rear, dead material)
  
  **CMS full shower simulation** $< 0.2 \%$

- system instabilities designed to be at the permill level $t \sim 3t_{cal}$
  - temperature stabilization $< 0.1 \degree C$
    
    \[ \frac{dL_Y}{dT} = -2.0\% / \degree C @ 18\degree C ; \frac{dM}{dT} \sim -2.3 \% / \degree C \]
  - APD bias stable at $\pm 20$ mV
    
    \[ \frac{dM}{dV} = 3\% / V \]

**Key issues to keep $c \sim 0.5 \%$:**

- light collection uniformity
- intercalibration by monitor and physics signals at 0.5 % including the radiation damage effect
Uniformity of light collection

- Focusing effect due to tapered shape of crystals (first seen and studied in L3)
- High index of refraction \((n=2.3)\) enhance the effect: \(\theta_c \approx 26^\circ\)

Uniformity can be controlled by depolishing one lateral face with a given roughness

PAY A LOSS IN LY
A non uniformity of the light collection in the shower max region may significantly contribute to the constant term in the energy resolution.

**Ideal light collection shape**

- Max Front \( \frac{d(LY)}{dX_0} = \pm 0.35\% / X_0 \)

- Lab measurement
  
  \( C_{fnuf} < 0.3\% \)

- Lab measurement

- FNUF < 0.3%/\( X_0 \)

- (crystals all polished)
**Calibration & Monitoring system**

- Initial calibration on test beam (as much crystals as possible)
- In situ calibration with physics events ($W \rightarrow e^+\nu, Z \rightarrow e^+e^-$) using $E/p$ from tracker allows at low luminosity in 35 days an intercalibration (single crystal) better than 0.3%.
- Monitoring of response evolution by light injection system

![Diagram of Calibration & Monitoring system]

LASER monitoring
- light injection
- $\lambda = 440$ nm and 500 nm
- 1/140 (80 Hz) beam gaps on 850 crystals
Electron vs Light signal

Recovery of damage if no beam

NB moderately rad hard crystals most suitable for monitoring studies

2002 Preliminary
Monitor: L3 10 years of follow-up

Response may change! Even if not foreseen

- system able to track the BGO response decrease (few%/year)
- porting of previous year calibration: 1.3%
- spread after Xe+Bhabha corrections: 0.8% from calibration in 1991

In 1999 0.5% from calibration after refinements of methods
Why pre-calibration of each single channel is desirable?
- Full system test
- Be ready as soon as possible for precision measurement independently from other CMS sub-detectors (precision on intercalibration has a direct impact on the constant term of the energy resolution)

A partial calibration is anyway mandatory to understand
- Geometrical effects (energy deposition depends on $\eta$)
- Effects of gaps between crystals, modules
- Thermal stability
- Gain stability in electronics chain
- Monitoring system
- MC simulation in all its aspects
- In situ calibration through reference regions
Compare Intercalibration

Preliminary results on 95 crystals - test beam 2002

SM not pre-calibrated: intercalibration @ t=0 from RC measurements @ 1MeV with different read-out

\[ \sigma = 5\% \]
ECAL distributed construction
ECAL Regional Centers

Submodule
- 10 crystals

Supercrystal
- 25 crystals

Dee
- 138 Supercrystals

36 Supermodules

4 Dees
Crystal quality insurance

Automatic control of:
- Dimensions
- Transmission (radiation hardness)
- Light yield and uniformity
Module assembly and test

Assemblaggio sottomoduli

Il primo modulo!

Inizio assemblaggio modulo

Sottomoduli assemblati

Il primo sottomodulo!
Transport of modules to CERN
Conclusions

- A challenging project
- Intense and rewording R&D effort performed
- Now in the construction phase
- Few years of construction (→ 2005)
- Few years to understand in detail the system behaviour
- Aiming to outstanding physics results