Pulse (Energy) & Position Reconstruction in the CMS ECAL
(Testbeam Results from 2003)

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On behalf of the CMS ECAL community
The Compact Muon Solenoid detector

Testbeam set-up in 2003:
- 2 supermodules (SM0/SM1) have been placed in the beam (electrons)
- Front-end electronics: FPPA(100) / MGPA(50) crystals equipped

R = 129 cm
\( \Delta z = 6,410 \) cm
Barrel = 61,200 crystals
## Two testbeam periods in 2003

Two sets of front-end electronics used: **FPPA** and **MGPA**

the new 0.25 μm front-end electronics

<table>
<thead>
<tr>
<th># gains</th>
<th>FPPA</th>
<th>MGPA</th>
</tr>
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<tbody>
<tr>
<td>4</td>
<td></td>
<td>3</td>
</tr>
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<table>
<thead>
<tr>
<th>SM (# equip. crys.)</th>
<th>FPPA</th>
<th>MGPA</th>
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<tbody>
<tr>
<td>SMO (100)</td>
<td></td>
<td>SM1 (50)</td>
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<thead>
<tr>
<th>period</th>
<th>FPPA</th>
<th>MGPA</th>
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<tbody>
<tr>
<td>long</td>
<td></td>
<td>short</td>
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<table>
<thead>
<tr>
<th>Electron energies (GeV)</th>
<th>FPPA</th>
<th>MGPA</th>
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<tbody>
<tr>
<td>20, 35, 50, 80, 120, 150, 180, 200</td>
<td></td>
<td>25, 50, 70, 100 (using PS heavy ion run)</td>
</tr>
</tbody>
</table>
Pulse (Energy) Reconstruction

Part 1

- A single pulse ... and how to reconstruct it
  (some testbeam specifics & evaluate universalities in the ECAL)
- Optimizing the algorithm
- Results
A single pulse

1) Photons detected using an APD
2) Signal is amplified
3) Digitization at 40 MHz (each 25 ns)
   3(4) gain ranges (Energies up to 2 TeV)
4) 14 time samples available offline

How to reconstruct the amplitude:

- **Analytic fit:** In case of large noise -> biases for small pulses
- **Digital filtering technique:** Fast, possibility to treat correlated noise
**Timing information**

**CMS:** Electronics synchronous w.r.t LHC bunch crossings

**Testbeam:** A 25 ns random offset/phase w.r.t the trigger

### Spread in Time of maximum response

- **Number of events**
- **Normalised** $T_{\text{max}}$
- **25 ns**

### Resolution versus mismatch

- **$\sigma(E)/E$ (%)**
  - **SMO/FPPA**
  - **Single Crystal 120 GeV**

- **Precision on $T_{\text{max}}$:**
  - **CMS:** jitter < 1 ns
  - **Testbeam:** < 1 ns (use 1 ns bins)
\[ \tilde{A} = \sum_{i} w_i \bullet S_i \]

- Weights computation requires knowledge of the average pulse shape
- Optimal weights depend on assumptions on \( S_i \)
Pulse Reconstruction Method

How to extract the optimal weights:

\[
\chi^2 = (\vec{S} - A \times \vec{F})^T \text{Cov}^{-1} (\vec{S} - A \times \vec{F})
\]

Sample heights \rightarrow Amplitude \rightarrow Covariance Matrix

Expected sample heights: F(t)

Minimize \( \chi^2 \) w.r.t. \( A \) assuming \{No pedestal, No correlations\}

- Timing: Define a set of weights for each 1 ns bin of the TDC offset
- Knowledge of expected shape required: shape itself, timing info and gain ratio

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Note: ● Shapes ($T_{\text{peak}}$, $\alpha$) are similar for large sets of (all) crystals

● $T_{\text{max}}$: 2 ns spread in the $T_{\text{max}}$ for all crystals (we account for it)

Analytic description of pulse shape:

$$f(t) = \left[ \frac{t - (T_{\text{max}} - T_{\text{peak}})}{T_{\text{peak}}} \right]^{\alpha} e^{-\alpha \left( \frac{t - T_{\text{max}}}{T_{\text{peak}}} \right)}$$

Could also use digital representation.
Optimization of parameters

- Optimization depends on particular set-up.
  For the testbeam:  
  - How many samples
  - Which samples

- Treatment of (correlated) noise
More samples:
- Precision (depends on noise and a correct pulse shape description)

Less samples:
- Faster & smaller data volume
- Reduce effects from pile-up & noise

Optimization of parameters for testbeam operation

**Total # samples**

**Which samples**

- Variance on $\langle A \rangle$ scales like sample heights → Use largest samples

Depend on TDC offset (decided per event)

- Use 5 samples
- Start at 1 sample before the expected maximum

### Graph

- **SMO/FPPA**
- **3x3 crystals 120 GeV**

![Graph showing relationship between number of samples and variance](image)
The (correlated) noise that was present in 2003 is under investigation and is treated off-line:

**Correlations between samples:** Extract Covariance matrix (pedestal run)

\[ \chi^2 = (\vec{S} - A \times \vec{F})^T \text{Cov}^{-1} (\vec{S} - A \times \vec{F}) \]

**Pedestals:** Use pre-pulse samples and fit Ampl. and Pedestal simultaneously

\[ \chi^2 = (\vec{S} - A \times \vec{F} - P)^T \text{Cov}^{-1} (\vec{S} - A \times \vec{F} - P) \]

An optimal strategy for this procedure is under investigation
Results using MGPA electronics

- 'No bias at small amplitudes
- Noise ≈ 50 MeV (per crystal)

\[
\frac{\sigma(E)}{E} = \frac{2.4 \%}{\sqrt{E}} \oplus \frac{142 \text{ MeV}}{E} \oplus 0.44 \%
\]

Final design of front-end electronics

4x4 mm² impact region

preliminary
Impact Position Reconstruction

Part 2

- Determination of the 'true' impact point
- Reconstruction of the impact point (2 methods)
- Conclusions
Precision on 'true' impact position

- A hodoscope system determines the e-trajectory (and impact point on crystal)

\[ \sigma(x) = \sigma(y) = 145 \, \mu m \]

Per orientation 4 points:

Per plane: 2 staggered layers with 1 mm wide strips
Impact on crystal centre: 82% in central crystal and 96% in a 3x3 matrix (use 3x3)

**General Idea:**

\[
\langle x \rangle = \frac{\sum_i W_i \cdot x_i}{\sum_i W_i}
\]

- The position of the crystal \((\eta_i, \phi_i)\) or \((x, y)\)
- Two methods using different weights: \(w_i = E_i\) or \(w_i = w_0 + \log \left( \frac{E_i}{\sum_j E_j} \right)\)

**Incident electron**

**Shower shape**

**Crystal size**
2.2 x 2.4 cm

**5x5 Energy Matrix**

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Defining THE position of the crystal:

- Crystals are off-pointing and tilted by in $\eta$ and $\phi$
- Depth of shower maximum is energy dependent

As an example: the balance point in X

**Side view**

**Data 120 GeV**

- Energy (ADC counts)
- Impact position (mm)

**Simulation**

- Energy (GeV)
- Balance Point (mm)

- 1.5 mm
Reconstruction Method 1: Linear weighting \( \omega_i = E_i \)

\[ \sigma = 620 \mu \text{m} \]

\[ \Delta Y (\text{reco.}-\text{true}) = \Delta Y (\text{reco.}-\text{true}) \text{ mm} \]

Best resolution: close to crystal edge

Worst resolution: max. energy fraction in central crystal

Requires a correction that is \( f(E, \eta, \varphi) \)
Reconstruction Method 2: Logarithmic weighting

\[ w_i = w_0 + \log \left( \frac{E_i}{\sum_j E_j} \right) \]  
\[ \text{(all weights should be} \geq 0.) \]

Minimal (relative) crystal energy included in computation

Optimal \( W_0 = 3.80 \) (min. crystal energy is 2.24% of the energy contained in the 3x3 matrix)

- Resolution is now more flat over the crystal surface
- no correction needed that is \( f(E, \eta, \varphi) \)

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Resolution on impact position using the logarithmic weighting method:

\[ \sigma_y (\mu m) = \frac{5040}{\sqrt{E}} \oplus 430 \]

Resolution in X slightly worse:
- Different staggering of crystals
- Different crystal dimensions
- 10% larger in X than in Y
- Different (effective) angle of incidence
Conclusions

- **Pulse (Energy) reconstruction:**
  - ECAL strategy to reconstruct pulses in the testbeam set-up evaluated
  - Optimized and existing 'universalities' are implemented.
  - Energy resolution reaches target precision using the designed 0.25 μm front-end electronics

- **Impact point reconstruction:**
  - Evaluated two approaches and extracted resolutions using real data
  - Above 35 GeV: $\sigma_x$ & $\sigma_y < 1$ mm
Backup slides
\[ W_i = \frac{f_i}{\sum_i (f_i^2)} \]

\[ w_i = (\lambda f_i + \gamma) \]

\[ \lambda^{-1} = \sum_i (f_i^2) - \left(\sum_i f_i^2\right)/n \]

\[ \gamma = -\frac{\lambda}{n} \sum_i f_i \]