CALICE silicon-tungsten electromagnetic calorimeter, $1 \times 1 \, \text{cm}^2$ granularity prototype testbeam and results

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Outline

- **General**

- **Si/W prototype**

- **Testbeam results**
  - position resolution, tracking performance
  - response map, inhomogeneity
  - transverse containment, Moliere radius

- **Summary**
General

- "1/3" of CALICE Si/W ECAL prototype
  - 3024 channels of $1 \times 1$ cm$^2$, 14 layers, 7.2 $X_0$
  - first testbeam at DESY with $e^-$ (Jan/Feb05), a lot of data collected

- data analysis
  - comprehensive understanding and debugging of the system before the next round of testbeams
  - also pilot-reference studies to be repeated as detector grows
  - results to discuss from studies on
    - position resolution, tracking performance
    - response map, inhomogeneity
    - transverse containment, Moliere radius
    - data-simulation comparison
full Si/W prototype (24 $X_0$)

- 30 layers $\times$ 18 cm $\times$ 18 cm, interleaved with 0.5 mm Si pads
- W absorber, 10+10+10 layers, 1.4 mm:2.8 mm:4.2 mm thick per respective layer
- readout by $1 \times 1$ cm$^2$ cells, total: 9720 channels
Calibration with cosmics

A typical channel: gaussian noise, landau signal
Cosmics

Run 1104860743 Event 133

Record Time = 17:47:59.737785 Tue Jan 4 2005, Type = 5 = event
DaoEvent::print() Event numbers in run 0, in configuration 0, in spill 0
Calibration with cosmics

- 2160 channels
  - mean = 48.4
  - $\frac{\text{sigma}}{\text{mean}} = 3.5\%$

- 2160 channels
  - mean = 8.2
  - $\frac{\text{sigma}}{\text{mean}} = 6.2\%$

- 10 layers (2160 channels) calibrated with cosmics (1 Mevents)
  (LLR-Paris, Dec04)

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CALICE-ECAL testbeam at DESY

- "30%" equipped Si/W prototype
  - i.e. 14 W layers (10 at 1.4mm + 4 at 2.8mm) interleaved with 18 × 12 matrix of active Si cells, **cellsize: 1 × 1 cm²**, total: 3024 channels
  - first testbeam at DESY with electrons during Jan/Feb05

- **in summary (configurations: position × energy × angle)**
  - position scan (center - edge - corner of wafers)
  - energy scan (mainly 1, 2, 3 GeV, some runs at 4, 5, 6 GeV)
  - angle scan (0°, 10°, 20°, 30°)
  - total: ~ 25 Mevents (~ 230 GB)
CALICE-ECAL testbeam at DESY

ECAL

3x2 wafer matrix

fans

cables to DAQ

XY table

layout at DESY T21

DriftChambers and installation courtesy of Tsukuba Univ. and Kobe Univ.

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"Response" vs cell threshold

- safe limit a threshold around 0.5 - 0.6 mip
- following analysis with threshold = 0.5 mip
"Tracking Calorimetry"

(not to scale)

e\(^{-}\) 1 GeV

cell threshold = 0.2 mip
"Tracking Calorimetry"

(not to scale)

e\textsuperscript{-} 1 \text{ GeV}

cell threshold = 0.5 mip
"Tracking Calorimetry"

(not to scale)

$e^{-}$ 2 GeV

cell threshold = 0.5 mip
"Tracking Calorimetry"

(Not to scale)

$e^- \ 3 \text{ GeV}$

cell threshold = 0.5 mip
Shower longitudinal profile

- shower maximum is contained
- odd/even asymmetry of construction observed
- showers better contained at 30°
Tracking - Residuals

ShowerX, Y from barycenter in ecal
TrackX, Y from 4 drift chambers
Position resolution

Residual RMS as a function of the number of ecal layers used

ECAL $0^\circ (7.2 \, X_0)$ e$^-$ 1 GeV

ECAL $0^\circ (7.2 \, X_0)$ e$^-$ 2 GeV

ECAL $0^\circ (7.2 \, X_0)$ e$^-$ 3 GeV

Residual RMS (mm)

Number of layers used

0 2 4 6 8 10 12 14

along X

along Y
Position resolution

ECAL 0° (7.2 $X_0$)

- Highly granular ECAL → excellent position resolution
Position resolution - undersampling

- do tracking by using only hits from every 2nd layer

- to investigate the tracking performance of an ecal with 5 layers $\times$ 2.8 mm W (instead of 10 layers $\times$ 1.4 mm W)

- expect position resolution to degrade by factor $\frac{\sigma_5}{\sigma_{10}} \approx \frac{\sqrt{10}}{\sqrt{5}}$

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Response map - center of wafer

ECAL 0° (7.2 X₀) e⁻ 1 GeV

ECAL 0° (7.2 X₀) e⁻ 2 GeV

ECAL 0° (7.2 X₀) e⁻ 3 GeV

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Response Inhomogeneity

- e⁻ 1 GeV: \( \sigma_{\text{mean}} = 5.6\% \)
- e⁻ 2 GeV: \( \sigma_{\text{mean}} = 4.8\% \)
- e⁻ 3 GeV: \( \sigma_{\text{mean}} = 5.1\% \)

Response Inhomogeneity along 40 × 40 mm² (Binsize: 1 × 1 mm²)

> response variation around the center of wafer
Response map - center/edge/corner of wafer
Wafer border

Non-active Zone ~ 1 mm

(C.LoBianco, LC-DET-2004-007)
Position scan along wafer borders

- **TrackX (mm)**
  - Values: -20, -15, -10, -5, 0, 5, 10, 15, 20

- **TrackY (mm)**
  - Values: -20, -15, -10, -5, 0, 5, 10, 15, 20

- **EventEnergy (normalised)**
  - Values: 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2

*ECAL 0° (7.2 X₀) e⁻ 1 GeV*

**Note:**
- alternate layers staggered along X (by 2.5 mm)
- dip is shallower and wider
- layers not staggered along Y
- dip is deeper and narrower

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Response Inhomogeneity

- Response Inhomogeneity along 40 x 40 mm² (Binsize: 1 x 1 mm²)
  - Center
    - \(\sigma\) mean = 5.6%
    - Mean = 175.1
  - Edge
    - \(\sigma\) mean = 7.3%
    - Mean = 171.3
  - Corner
    - \(\sigma\) mean = 9.7%
    - Mean = 162.2

- Response variation around the center/edge/corner of wafer

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Transverse containment (Moliere radius)

\[ \text{Energy Contained (\%)} \]

\[ \begin{array}{c|c|c|c|c|c|c|c|c|c|c|c} \hline \text{Radius (mm)} & 0 & 10 & 20 & 30 & 40 & 50 & 60 & 70 & 80 & 90 & 100 \\ \hline \text{Energy Contained (\%)} & 90 & 91 & 92 & 93 & 94 & 95 & 96 & 97 & 98 & 99 & 100 \\ \end{array} \]

1 GeV \( e^- \), 2 GeV \( e^- \), 3 GeV \( e^- \)

\( \text{ECAL} \ 0^\circ (7.2 X_0) \)

\( \text{DATA} 7.2 X_0 \)

\( \text{SIM} 7.2 X_0 \)

\( \text{SIM} 24 X_0 \)

\( \text{data-simulation comparison} \)

\( \text{results expected for the 24} \ X_0 \text{ prototype} \)

\( \text{e.g. 1 GeV} \ e^- \text{ shower "contained" at} \)

\( \begin{array}{l|l} \text{90\%} & \text{within radius 16 mm} \\ \text{95\%} & \text{23 mm} \\ \text{99\%} & \text{50 mm} \end{array} \)

\( \text{REMINDER:} \)

\( \text{for an infinitely long and wide calorimeter} \)

\( \text{shower contained at} \)

\( \begin{array}{l|l} \text{90\%} & \text{within radius} \sim 1 R_M \\ \text{95\%} & \text{2} R_M \\ \text{99\%} & \text{3.5} R_M \\ \end{array} \)

( for solid \( W \), \( R_M \approx 10 \text{ mm} \) )

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Reminder (High Granularity Calorimetry)

- "particle flow paradigm" requires
  - highly granular EM and HADR calorimeters to allow very efficient pattern recognition for excellent shower separation and pid within jets to provide excellent jet reconstruction efficiency
  - strong interplay between hardware and software

- CALICE roadmap (concepts+questions → answers and optimal design)
  - build ECAL and HCAL prototypes and do extensive individual and combined testbeam studies
  - demonstrate proof of technology/detector concept(s)
  - debug-characterise-optimise detector performance
  - test-validate-improve simulation codes and shower packages
Data-simulation comparison (energy per hit)

(studies by D.Ward)

▷ good agreement between data and simulation
▷ G4.8.0 improved wrt G4.7.1
Data-simulation comparison (shower profile)

(studies by D. Ward)

- Good agreement between data and simulation
- G4.8.0 improved wrt G4.7.1

![Graph showing #of hits vs distance(mm) from shower barycenter](image1)

![Graph showing energy vs distance(mm) from shower barycenter](image2)
Summary

• "1/3" of CALICE Si/W ECAL prototype
  
  : 3024 channels of $1 \times 1 \text{ cm}^2$, 7.2 $X_0$, 14 layers

  : first testbeam at DESY with $e^-$ (Jan/Feb05)

  : results shown from studies on
    ▸ position resolution, tracking performance
    ▸ response map, inhomogeneity
    ▸ transverse containment, Moliere radius

  : further data analysis in progress

• next steps
  
  : testbeams at DESY and at CERN with ECAL completed
    and in combination with HCAL

  : see also talks from G.Gaycken(ECAL) and F.Sefkow(HCAL)
BACKUP SLIDES
ECAL board

6 active wafers
- 36 silicon PIN diodes each → 216 channels per board.
- Diode size: $1 \times 1\,\text{cm}^2$.

Calibration chips
- 2 calibration switches chips.
- 6 calibration channels per chip.
- 18 diodes per calibration channel.

Front-End chip
- 12 FLC-PHY3 front-end chip
  - 18 channels / chip
  - 13 bit dynamic range

Line buffers
- To DAQ part
- Differential.

PCB:
- 14 layers
- 2.1 mm thick
- Made in Korea

(G.Gaycken)
**CALICE readout card**

- Calice Readout Card (CRC) VME board
  - Modified CMS silicon tracker readout board
  - Does VFE PCB control, digitisation and data buffering
  - Also does trigger control

Diagram showing Virtex-II FPGAs, 16-bit dual ADCs, and 8MByte buffer.

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General

► particle flow paradigm
  - highly granular EM and HADR calorimeters to allow very efficient pattern recognition for excellent shower separation and pid within jets to provide excellent jet reconstruction efficiency

► CALICE ECAL(Si/W) and HCAL(Scint/Fe, RPC/Fe) prototype studies
  - debug technology/detector concept(s)
  - detector characterisation
  - test "particle flow paradigm", interplay between hard/soft-ware
  - test-validate-improve simulation codes and shower packages

► details about CALICE Si/W ECAL prototype follow
"Response" to electrons

- no weighting, no event selection, no tracking
- showers better contained at 30°
no weighting, no event selection, no tracking

\( dx = \text{CellX} - \text{BarycenterX} \)

distance between peaks = 1 cm = transverse granularity
Position scan

ShowerX,Y from barycenter in ecal
TrackX,Y from 4 drift chambers
Position scan - center of wafer

ECAL 0° (7.2 X₀) e⁻ 1 GeV

BinWidth: 2e-02
Position scan - center of wafer

ECAL $0^\circ (7.2 \, X_0)$  \(e^- \, 1 \, \text{GeV}\)

Event Energy per mm (au)

BinWidth: 1e-01

Track X (cm)

Track Y (cm)

PRELIMINARY
Position scan - edge of wafer

ECAL 0° (7.2 $X_0$)  $e^-$ 1 GeV

BinWidth: 2e-02
Position scan - edge of wafer

ECAL 0° (7.2 $X_0$)  e⁻ 1 GeV

PRELIMINARY
Position scan - corner of wafer

ECAL 0° (7.2 X₀)  e⁻ 1 GeV

BinWidth: 2e-02
Position scan - corner of wafer

ECAL 0° (7.2 X₀)  e⁻ 1 GeV

- alternate layers staggered along X
- dip is shallower and wider

- layers not staggered along Y
- dip is deeper and narrower

PRELIMINARY
Transverse containment (Moliere radius)

Data-simulation comparison

- Results expected for the 24 $X_0$ ecal prototype
Transverse containment (Moliere radius)

\[ \text{Energy Contained} (\%) \]

\[ \begin{array}{c|c|c|c|c|c|c|c|c|c|c|c|c} 
0 & 10 & 20 & 30 & 40 & 50 & 60 & 70 & 80 & 90 & 100 \\
\hline
90 & 91 & 92 & 93 & 94 & 95 & 96 & 97 & 98 & 99 & 100 \\
\end{array} \]

\[ \text{Radius (mm)} \]

\[ \text{ECAL } 0^\circ (7.2 \times 7) \]

- e^− 1 GeV
- e^− 2 GeV
- e^− 3 GeV

\[ \text{Energy Contained} (\%) \]

\[ \begin{array}{c|c|c|c|c|c|c|c|c|c|c|c} 
0 & 10 & 20 & 30 & 40 & 50 & 60 & 70 & 80 & 90 & 100 \\
\hline
90 & 91 & 92 & 93 & 94 & 95 & 96 & 97 & 98 & 99 & 100 \\
\end{array} \]

\[ \text{Radius (mm)} \]

\[ \text{ECAL } 0^\circ (7.2 \times 7) \]

- center
- edge
- corner

\[ \text{slight degradation if impact is along edge/corner of wafer} \]

\[ \text{e.g. } 1 \text{ GeV } e^- \text{ shower "contained" at} \]

\[ \begin{array}{c|c|c|c} 
: 90\% & \text{within radius } 16 \text{ mm} \\
: 95\% & 23 \text{ mm} \\
: 99\% & 50 \text{ mm} \\
\end{array} \]

REMINDER: for an infinitely long and wide calorimeter

<table>
<thead>
<tr>
<th>shower contained at</th>
<th>90%</th>
<th>within radius</th>
<th>95%</th>
<th>~ 1 ( R_M )</th>
<th>99%</th>
<th>~ 2 ( R_M )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(for solid W, ( R_M \approx 10 \text{ mm} ))</td>
<td></td>
<td></td>
<td></td>
<td>( \approx 3.5 \text{ } R_M )</td>
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