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Simulated Performance of the SiD Digital ECAL Based on Monolithic Active Pixel Sensors

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on behalf of
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“The SiD Digital ECAL Based on Monolithic Active Pixel Sensors”, 10.3390/instruments6040051, Instruments, 6, 51 (2022)
SiD Digital ECAL Based on MAPS

- Upgrade ILC TDR design to replace sensors with 13 mm\(^2\) analog pixels with 25 x 100 um\(^2\) (or 25 x 50 um\(^2\)) digital pixels.

- How well can we measure energy and shower structure with digital system:
  - Compared to SiD baseline of analog measurements.
  - Can the detailed structural measurements be used to improve measurement?
  - Would a neural net optimization offer an improvement?

- What are the limits of transverse separation and measurement?
Large area MAPS for SiD tracker & ECal

Benefits of large-area MAPS:

- Standard CMOS foundry, low resistivity: cost ↓
- Sensing element and readout electronics on same die
  - In-pixel amplification: noise ↓, power ↓
  - No need for bump-bonding: cost ↓
- Area > 10x10 cm$^2$ → enable O(1) m$^2$ modules

Several design challenges:

- Large on-die variations, mismatch
- Yield
- Stitching layout rules
- Distribution of power supply
- Distribution of global control signals/references

Goals of R&D: find solutions and explore novel design techniques

L. Rota
# Main specifications for Large Area MAPS development

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min Threshold</td>
<td>140 e-</td>
<td>0.25*MIP with 10 μm thick epi layer</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>7 μm</td>
<td>In bend plane, based on SiD tracker specs</td>
</tr>
<tr>
<td>Pixel size</td>
<td>25 x 100 μm²</td>
<td>Optimized for tracking (note: 25 x 50 μm²)</td>
</tr>
<tr>
<td>Chip size</td>
<td>10 x 10 cm²</td>
<td>Requires stitching on 4 sides</td>
</tr>
<tr>
<td>Chip thickness</td>
<td>300 μm</td>
<td>&lt;200 μm for tracker. Could be 300 μm for EMCal to improve yield.</td>
</tr>
<tr>
<td>Timing resolution (pixel)</td>
<td>~ ns</td>
<td>Bunch spacing: C^3 strictest with 5.3-&gt;3.5 ns; ILC is 554 ns</td>
</tr>
<tr>
<td>Total Ionizing Dose</td>
<td>100 kRads</td>
<td>Total lifetime dose, not a concern</td>
</tr>
<tr>
<td>Hit density / train</td>
<td>1000 hits / cm²</td>
<td></td>
</tr>
<tr>
<td>Hits spatial distribution</td>
<td>Clusters</td>
<td>Due to jets</td>
</tr>
<tr>
<td>Balcony size</td>
<td>1 mm</td>
<td>Only on one side, where wire-bonding pads will be located.</td>
</tr>
<tr>
<td>Power density</td>
<td>20 mW / cm²</td>
<td>Based on SiD tracker power consumption: 400W over 67m²</td>
</tr>
</tbody>
</table>

L. Rota

25 x 100 μm²
ECal performance same as 50 x 50 μm²

SiD Tracker and the ECal

RDC3 talks today
A. Habib & C. Vernieri
Model of longitudinal structure of SiD ECAL

Total = 27 $X_0$

Minimize sampling gap to achieve optimal Moliere radius (14 mm) & shower separation

20 layers of 2.243 mm W + 1 mm sampling gap
10 layers of 4.486 mm W + 1 mm sampling gap

20 GeV $\gamma$ average profile

Incident Particle

HCAL
10 GeV Shower in 25 x 100 μm²
Resolution vs. Energy (hits & mips)

Resolution vs. Energy
(hits & mips)

Pixel hit threshold = 1 keV = 270 e’s

Mip threshold = 0.1 MeV

Note - mip is counted once, in pixel it first passes through.

10 GeV
5.8%

10 GeV
3.4%

16.4% / √E + 2.0%
9.8% / √E + 1.1%
Example of hit distribution in a MAPS

- Most hits isolated
  - Single hit cluster
  - Multiple hit clusters
    - Often single mip, or no mip
  - Counting clusters should reduce hit fluctuations

Cluster definition: Collection of hits in contact

- Hits no Mips
- Mips

Cluster Size for Mip Counts

- 10 GeV γ

Cluster Size

Yellow - hit w/o mip
Others - 1 or more mips

Hitmap Definition:
Collection of hits in contact

Event = 22
Layer = 10
Cl. Count = 2
Cl. Mips = 1
Image Count = 24
Image Mips = 17

Cluster Num. = 405
y0 = 16.5
z0 = -1.0

mip = e± > 0.1 MeV
hit = > 1 keV or 270 e's

Yellow - hit w/o mip
Others - 1 or more mips
Resolution vs. Energy (hits/clusters/mips)

Resolution vs. Energy (hits/clusters/mips)

10 GeV
- 5.8% for hits
- 4.9% for clusters

Pixel hit threshold = 1 keV = 270 e’s

Simple cluster performance is better than hit counting.

10 GeV
- 16.4% / $\sqrt{E} \oplus 2.0\%$
- 13.7% / $\sqrt{E} \oplus 2.0\%$
- 9.8% / $\sqrt{E} \oplus 1.1\%$
All Clusters are not the same

- Some clusters are numerous mips.

Cluster size 15
Either few mips
Or Many mips

$e^+ > 0.1$ MeV for only 1 mip
Mips/cluster 10 GeV $\gamma$S - 2000 showers

- Size 1 clusters
- Size 2 clusters
  $W_t = a \exp(-bR) + c$
  $a, b, c = f(ClSz)$
- Size 3 clusters
- Size 4 clusters
- Size 5 clusters
  Large mip clusters near shower axis
- Size 6 clusters
Apply weight to clusters:

\[ \text{RadWt} = a \exp(-bR) + c \]

\[ a, b, c = f(\text{Clsiz}) \]
Resolution vs. Energy (hits/clusters/mips)

Resolution vs. Energy (hits/clusters/mips) & weighted clusters.

10 GeV 4.9%

10 GeV 4.3%

Cluster properties weighting improves performance.
Neural net cluster weighting based on

1. Three input parameters = Cluster size, layer num, shower radius
2. Five input parameters = Add cluster length in Y and Z

TRAINING - 10 GeV
2000 events
2,502,000 hits
1,878,999 clusters

# Store model to file
model.save('modelRegression%s.h5'%Efact)
model.summary()

# Book methods
factory.BookMethod(dataloader, TMVA.Types.kPyKeras, 'PyKeras',
'H:
V:VarTransform=D,G:FilenameModel=modelRegression%s.h5:FilenameTrainedModel=
trainedModelRegression%s.h5:NumEpochs=20:BatchSize=32%(Efact,Efact)
Weighted function vs. TMVA neural net (10 GeV γs)

\[ \text{Weighted function: } Wt = f(Clsz, R) \]

\[ \text{TMVA function: } \text{TMVA mips} = f(Clsz, Layr, R) \]

\[ \text{TMVA function: } \text{TMVA mips} = f(Clsz, Layr, R, dY, dZ) \]

- Wt = 4.3%
- TMVA mips = 4.4%
- TMVA mips (with additional parameters) = 4.3%

Gaussian fit for unweighted clusters: 4.3%
### Results: Energy Resolution

<table>
<thead>
<tr>
<th>Energy</th>
<th>1</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>clusters</td>
<td>13.8%</td>
<td>10.1%</td>
<td>6.6%</td>
<td>4.9%</td>
<td>3.7%</td>
<td>2.7%</td>
</tr>
<tr>
<td>wtd clusters</td>
<td>12.3%</td>
<td>8.8%</td>
<td>5.7%</td>
<td>4.4%</td>
<td>3.2%</td>
<td>2.2%</td>
</tr>
<tr>
<td>3 par TMVA</td>
<td>12.6%</td>
<td>9.5%</td>
<td>6.2%</td>
<td>4.4%</td>
<td>3.4%</td>
<td>2.2%</td>
</tr>
<tr>
<td>5 par TMVA</td>
<td>12.8%</td>
<td>9.4%</td>
<td>5.9%</td>
<td>4.3%</td>
<td>3.1%</td>
<td>2.2%</td>
</tr>
</tbody>
</table>

- Weight fits for 2, 10, 50 GeV; extrapolated for 1, 5, 20 GeV.
- NN optimized for each energy
- 3 par = cluster size, layer, radius
- 5 par = cluster size, layer, radius, dY, dZ

Weighted clusters already achieve performance of this neural net.
Transverse Shower Structure

10 GeV
Multi-shower of SiD MAPS compared to SiD TDR

$40 \text{ GeV } \pi^0 \rightarrow \text{two } 20 \text{ GeV } \gamma$'s

SiD TDR hexagonal sensors
13 mm$^2$ pixels

New SiD fine pixel sensors
25 µm x 100 µm pixels
Shower Image, Event 7

- Tracker Charged, p>1.0 GeV
  E_max = 24.4 GeV
  num = 13

- MC Gamma, E>0.5 GeV
  E_max = 9.7 GeV
  num = 11

h \rightarrow Zh
Z \rightarrow jets
h \text{ invisible}
γ’s in jet / SiD baseline ECal (13mm² pixels)

- 13 mm² pixels of analog SiD ECAL
- 5000x granularity with digital MAPS ECal
- Upcoming integration into SiD simulation will define scale of improvement?
Conclusion

❖ Application of monolithic active pixel sensors (MAPS) to SiD digital ECal offers excellent performance:
  ❖ Energy measurement
  ❖ Transverse energy containment & multiple shower separation
❖ The well defined structure of EM showers allows simple algorithmic improvement in energy measurement.
❖ Neural nets have been studied to improve energy measurement:
  ❖ They have not yet provided improvement over the “informed” algorithm.
❖ Future - simulation of full SiD detector with high granularity of MAPS ECal