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The SiD Digital ECAL based on Monolithic Active Pixel Sensors

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on behalf of the SiD MAPS Collaboration (M. Breidenbach, L. Rota, et al.)
The SiD Digital ECal based on Monolithic Active Pixel Sensors

- **SiD TDR ECal** design successfully tested in 9 layer SLAC beam test.
  - 13 mm² pixels on 6 inch wafers
  - 1024 pixels per wafer
  - KPiX readout bump-bonded to sensor

- **Improved** ECal design under development based on 25 μm x 100 μm MAPS
Large area MAPS for SiD tracker & ECal

Benefits of large-area MAPS:

- Standard CMOS foundry, low resistivity: \textit{cost} ↓
- Sensing element and readout electronics on same die
  - In-pixel amplification: \textit{noise} ↓, \textit{power} ↓
  - No need for bump-bonding: \textit{cost} ↓
- Area > 10x10 cm\(^2\) \(\rightarrow\) 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
SiD Digital ECal based on Silicon MAPS
Model of longitudinal structure of SiD ECAL

Total = 27 X₀

Minimize sampling gap to achieve optimal Moliere radius and 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 γ average profile
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></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>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>

SiD Tracker and the ECAL  

L. Rota
ILC time structure & operation phases

Phases:

- **Bunch repetition:** 200 ms
- **Bunch train:** 727 µs
- **Bunch spacing:** 554 ns

Duty-cycle < 1%

1312 bunches

Description:

- **Idle:** non vital resources kept in power saving mode
- **Wake:** all resources get ready to run
- **Integration:** analog processing in pixels active. No digital activity, balcony in power saving
- **Readout:** zero-suppressed readout & data transmission. Matrix in power saving

L. Rota
• Expected 1 hit/pixel/bunch train \(\rightarrow\) integrate charge through whole bunch train \(\rightarrow\) store 1 hit/pixel

• Segmentation of pixel front-end connected to common digital logic. See also CLICTD [1]

• Optimal segmentation of pixel front-ends will depend on sensor performance


L. Rota
Power during integration phase

Phase:

- Avg power consumption reduced by power-cycling … but **peak** current draw is not!
- Assuming 1µA/pixel, current draw is ~16 A
- Resistance of metal lines not negligible over 10 cm → significant voltage drop

Possible strategies:
- Bypass caps distributed over sensor
- EMCal flat cable distributes power to all reticule bump connections
- Re-distribution layer with thick metal deposited on-top
- Discuss with foundry about having more/thicker metal layers

**Need to investigate strategies on how to cope with shorts:**
Add “switches” for each column/cluster → if a short detected, DAQ disables the column during initial power-up sequence

L. Rota
Design an **asynchronous** readout logic with **zero-suppression**:

- Only pixels with HIT information are read-out by balcony
- Need to transmit data from pixel to balcony over ~10 cm lines, with large interconnection RC → minimize bit transitions → **power ↓**
- Remove clock → **power ↓**
- Handshaking between pixel and balcony ensures proper data transmission even with large on-die variations
- First simulations done, data throughput meets specs: ~200 ns to transmit one “hit” from pixel to balcony
Large area MAPS: next steps

- Join WP1.2 collaboration at CERN
- Design 1.5x1.5 mm² prototype with few pixels to test sensor + front-end
- Submission of first prototype in early 2022
- Study sensor performance on TowerJazz 65 nm process
  - TCAD simulations to optimize sensor design
  - Feedback from WP 1.2 measurements done at CERN
- Study bunch-tagging strategy
  - Analog-based: ramp, with low-res ADC in balcony (~8 bits)
  - Digital-based: local DLL for Time-to-Digital Conversion

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Gap Structure with MAPS

ONE CABLE IN GAP DESIGN

Gap structure with MAPs on one cable (or pcb). Requires bump bonding

This may well need adjustment following more cable design

M. Breidenbach
Sampling Gap Simulation - SiD MAPS Digital ECal

Geant4 simulated silicon gap structures

Assumption:
Pixel threshold = 1 keV ≈ 270 e’s

Future:
More detailed gap model

Typical hits distribution
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 $\mu$m x 100 $\mu$m pixels
Linearity of response (counting hits in $\gamma$ showers)

Non-linearity due to differing response and counting in thin ($0.7 \times X_0$) and thick ($1.4 \times X_0$) layers (and uncorrected leakage).
Hits resolution

ILC TDR anticipates $\frac{17 \%}{\sqrt{E}} \oplus 1 \%$ for the SiD SiW ECal; but we can do better.
Ultimate goal is to count mips based on hit distribution. Potential to improve resolution compared to hit count.
Hits appear in clusters (size 1, 2, 3,...)

Some examples

Many clusters have 1 mip
(black - first appearance of mip)

20 GeV γ
Mips per cluster

Many clusters contain more than 1 unique mip

Cluster Mips -

20 GeV $\gamma$

Entries: 3888838
Mean: 0.7366
Std Dev: 0.824
Cluster summary (20 GeV $\gamma$)

Yellow - hit w/o hit
Others - 1 or more mips
Energy resolution from counting clusters

Improved compared to hit resolutions:

\[
\frac{17\%}{\sqrt{E}} \quad (10\text{ GeV})
\]

\[
\frac{18\%}{\sqrt{E}} \quad (20\text{ GeV})
\]
Cluster performance is simple cluster counting.

When cluster properties are taken into account the performance will improve, based on preliminary studies.

Resolution vs. Energy (hits/clusters/mips)
40 GeV $\pi^0 \rightarrow$ two 20 GeV gammas
40 GeV $\pi^0$ reconstruction
Two 10 GeV electron showers - 1 cm separation

Clusters in early layers (5.4 \(X_0\) of 27 \(X_0\))
Performance summary
Two nearby 10 GeV electrons in SiD MAPS ECal

- Excellent performance!
- Note - very little optimization so far
Counting showers: random number of electrons
Spatial distribution rms = 8 mm

Clusters in early layers (5.4 X₀ of 27 X₀)

<table>
<thead>
<tr>
<th>Showers</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>152</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>2</td>
<td>0</td>
<td>1</td>
<td>145</td>
<td>3</td>
<td>0</td>
<td>0</td>
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<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>70</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>24</td>
<td>0</td>
</tr>
</tbody>
</table>
Reconstructing positions of Random number distribution of electrons

SiD MAPS Digital ECal

$\Delta y$ (True-meas) 175 $\mu$m

$|\Delta|$ (true-reconstruction) rms = 118 $\mu$m

$\Delta z$ (True-meas) 156 $\mu$m

4 electrons 4 recon. showers
Mips/cluster and shower radius dependence

Cluster details “sense” number of mips:
- Radius from shower axis;
- Longitudinal position (layer number);
- Cluster shape.

Analysis using these parameters improves cluster resolution in preliminary studies.

Average mips vs. Cluster Size

Mips/cluster vs. Radius from shower axis

20 GeV γ

10 GeV electron
All cluster sizes

10 GeV electron
Size 4 clusters
Ongoing studies - Sensor development and shower analysis

- Sensor development progressing.
- Shower performance studies advancing:
  - Various cluster features “sense” mip count in “large” clusters.
  - So far, each cluster is assumed to hold one mip, but cluster features show potential to improve this assumption:
    - Based on radial position in shower;
    - Based on longitudinal position in shower;
    - Based on shape of cluster;
    - THESE ARE ALL BEING INVESTIGATED, along with other aspects that show promise for improved precision.
- WE ARE LOOKING FOR COLLABORATORS - JOIN US!