Detailed Measurements of Shower Properties in a High Granularity Digital Electromagnetic Calorimeter

Naomi van der Kolk for the ALICE-FoCal Collaboration
• **Si-W ECAL** using Monolithic Active Pixel Sensors (MAPS) PHASE2/MIMOSA23 produced at IPHC

• **Digital ECAL**: count the number of pixels above threshold

• Average pixel occupancy should be $<<1$

• For particle densities of $10^3$/mm$^2$ in the shower core need pixels of the order 50 - 100 $\mu$m

• 24 layers of $0.97 \times_0$ (3 mm W, 1 mm sensor) with active area of 4x4 cm$^2$, with pixel size 30 $\mu$m: 39 M pixels total

• Moliere radius $\sim$ 11 mm

• **Demonstrate digital calorimetry**

• **Test MAPS for calorimeter application**

• **Ideal for testing particle showers in detail (electromagnetic and hadronic)**
The FoCal in ALICE

- **Direct photon production** in p-Pb collisions at forward rapidities offer a clean probe for parton distribution functions and gluon saturation
- In order to detect direct photons, they must be separated from **decay photons** from (mostly) $\pi^0$
- At high energies and high rapidities **particle densities** will be very high
- Decay photons from high energy $\pi^0$ will have a small separation angle
- In order to separate such photon showers in an ECAL a **very high granularity** is needed
- R&D prototype for a **proposed upgrade** of the ALICE forward calorimeter; FoCal
- Recently submitted arXiv:1708.05164

More details in the talk by Thomas Peitzmann at 16:50 today
## Test beam results (2014)

<table>
<thead>
<tr>
<th>Site</th>
<th>Particle type</th>
<th>E (GeV)</th>
<th>Nevts</th>
</tr>
</thead>
<tbody>
<tr>
<td>DESY T22</td>
<td>e⁺</td>
<td>2, 3, 4, 5.4</td>
<td>9.5 k</td>
</tr>
<tr>
<td>CERN SPS T8</td>
<td>e⁺, π⁺</td>
<td>30, 50, 100</td>
<td>30 k, 30 k, 80 k</td>
</tr>
<tr>
<td>CERN SPS T8</td>
<td>e⁻, π⁻</td>
<td>244</td>
<td>16 k</td>
</tr>
</tbody>
</table>

17% dead area

Average noise rate $10^{-5}$/pixel
Calibration

- Use e.m. shower shapes to calibrate and correct for dead areas and sensor sensitivity
- Calculate hit density in rings around the shower centre
- Equalise sensitivity of the 4 sensors within each layer
- Equalise layers with Gamma function fit \( N(t) = N_0 b \frac{(bt)^{a-1}e^{-bt}}{\Gamma(a)}(t = x/X_0) \)

![Diagram showing calibration process](Image 1560x600 to 1836x862)

![Graph showing hit density before and after calibration](Image 2234x1036 to 2290x1092)

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Detailed Measurements of Shower Properties in a High Granularity Digital Electromagnetic Calorimeter - N. van der Kolk - CHEF 2017
Geant4 simulation

- Prototype has been implemented in Geant4, ideal and real detector
- Simple charge diffusion model implemented
- Recombination modelled by attenuation length
- Charge threshold for pixels
- Threshold and attenuation length tuned to data (not very sensitive)
Longitudinal Profiles

- Based on the integral of the hit density
- Normalised distributions
- Deeper showers at higher energies
Comparison to Geant4

- Larger number of hits in data in the first few radiation lengths
- Shower maximum reached earlier in data compared to MC

![Graph showing comparison between data and MC](image)

**Longitudinal Profile**
- Number of hits vs. Depth
- Data and MC for 100 GeV and 5.4 GeV

**Shower Maximum**
- Shower maximum position vs. Energy
- Data/MC ratio for 100 GeV and 5.4 GeV
- Simulation, DESY data, SPS data

**Linearity**
- ln(E) vs. Energy
- E (8.11 MeV) - 0.5
Longitudinal Profiles

- Average hit density as a function of depth for different radial positions
- Maximum hit density deeper for increasing ring radius
- Saturation in shower core (< 0.1 mm) at high energies
Radial Profiles

- Average hit density as a function of radius for different layers
- Profiles broaden with depth
- Increase up to shower maximum and then decay
Comparison to Geant4

- In data a larger hit density in the shower core is seen in the first few layers.
- In the MC the profiles are narrower compared to data.
  - Does the MC produce a too low hit density in the core?
  - Caused by the imperfect charge sharing implementation in the simulation?
Different Geant4 EM model implementations

- For the CALICE DHCAL _EMY physics list showed better performance

- Investigate the difference of several EM implementations on the showers in FoCal: standard, _EMY (option 3) and _EMZ (option 4)

- Very small differences: _EMY and _EMZ 3% (4 GeV) - 4% (30 GeV) less total hits
  In longitudinal profile over large range
  In lateral profile in shower core (<1 mm) and periphery

- Qualitative differences in same area as the differences with data

WORK IN PROGRESS
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![Graphs showing comparisons between different EM models at 4 GeV and 30 GeV](image_url)
Particle identification

• Good selection of electrons vs pions possible in test beam data based on the number of hits

• Higher energy pions can generate the same number of hits as lower energy electrons

• Investigate other selection criteria applicable in a real experiment:
  
  Interaction layer
  Hit density in shower core 3D shower shape (Master thesis just started)

100 GeV mixed (electron + pion) data. The fraction of electrons and pions is determined from a template fit based on MC simulations

Interaction layer of pions with a similar number of hits as 30 GeV electrons

Interaction layer of electrons at different energies, mostly before 5th layer

Interaction layer \( l \) is defined as: \( N_{\text{Hits}} > 30 \) for 3 layers or 2 consecutive layers in the range \([\text{layer } l, \text{layer } (l+4)]\)
Fit to central radial hit density

- Fit a linear function to the log of the radial hit density in the first 5 mm from the centre
- Compare fit parameters $a$ (slope) and $b$ (constant) between electrons and pions
- Distribution for pions much more spread out
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Conclusion

• Successful test of the MAPS prototype

• proof of principle of a digital pixel calorimeter

• new prototype based on ALPIDE chip underway

• Unprecedented detail of spatial distribution of e.m. showers

• Ideal for testing MC models in detail; electromagnetic but also hadronic models (ongoing)

• Identify particle type based on shower observables (ongoing)
Thanks for your attention
MIMOSA23 chip

- Monolithic Active Pixel Sensor
- Chip size: 19.52 mm x 20.93 mm
- Active area: 19.2 mm x 19.2 mm
- Pixel pitch: 30 μm, 640 x 640 pixels (=409600/chip)
- Readout frequency: 160 MHz
- 1 MHz rolling shutter, 640 μs integration time
Response

- Response calculated via integration of calibrated radial hit density
- Good linearity
Energy resolution

- Good energy resolution

\[ \frac{\sigma}{E} = \frac{30}{\sqrt{E(\text{GeV})}} + \frac{6.3}{E(\text{GeV})} + 2.8 \]

- Proof of principle of digital calorimeter

Figure 19. Energy resolution as a function of beam energy for electrons. As in figure 18 the data are compared to simulations using both the real and an ideal detector. Simulation and the experiment is partly due to the energy spread of the testbeam (1.5%). Another cause may be the assumed homogeneity of the sensitivity of the sensors in the simulation. As already shown in figure 8 left there is also a discrepancy in the simulation of the cluster size, which points in the same direction.

The very narrow lateral distributions shown in figure 13 suggest the possibility to use only the hits within a certain radius \( R \) from the shower centre. This is explored by applying an upper limit to \( R \) in equation 4.13. In this way one can retrieve information from nearby showers, even closer than a Molière radius. Figure 20 shows the resolution and the response as a function of this limit radius \( R \). One can see that down to half \( R_M \) the resolution and the response are hardly affected.
Position resolution

- Position resolution determined from the spread in the residuals of the centre of gravity (layers 1 - 23) compared to the first layer (layer 0)

- Resolution reached smaller than pixel size

- Excellent 2 shower separation possible

![Position Resolution](image)

Energy(GeV) 0 50 100 150 200 250

Position Resolution(µm)

0 25 50

Data(e⁻/e⁺) Simulation

In both figures the results of two simulations are also shown. They are based on the procedure described in section 3: "ideal detector" uses all sensors, "real detector" excludes all not working sensors, channels and pixels. The first shows what would be ultimately achievable with this technique, given the size and segmentation of the prototype. The discrepancy between the second
Excellent two shower separation

- Shower separation down to ~5 mm possible

244 GeV single event
Shower core

• Response and energy resolution possible from the shower core only \((r = 5 \text{ mm})\)
  Integral in cylinder around the shower centre

• Separation power to \(~0.5 R_M\) possible

![Graphs showing resolution and response as a function of the radius of the core for different energies.](image)