Test beam performance of a digital pixel calorimeter

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Digital Pixel Calorimeter

- current R&D performed in the context of the Bergen R&D collaboration
- proton CT scanner for particle therapy
  - sampling calorimeter with high-granularity Monolithic Active Pixel Sensors (MAPS)
  - Al absorber + MAPS
  - to determine proton range and stopping power

→ Similar detector principle usable in High-Energy Physics
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- **Digital Pixel Calorimeter for High-Energy Physics**
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  - number of pixels above threshold in proportion to deposited energy
  - good position resolution
  - 3D shower shape measurement
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**FoCal-E (Forward EM-Calorimeter) in ALICE**

- hybrid of digital pixel layers and lower-granularity layers
- High-granularity layers (digital pixels)
  - for two-shower separation
- Low-granularity layers (analog readout pads)
  - for energy measurement
- discriminate $\pi^0/\gamma$ at high energy
  - separate photon pairs with distance < 5 mm
  - small Molière radius and high-granularity
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This Presentation
ALPIDE MAPS

- ALPIDE CMOS MAPS
  - Chip size: 30.00 mm x 15.00 mm
  - Pixel matrix: 1024 x 512 (~500k pixels / chip)
  - Active area: 29.94 mm x 13.76 mm
  - Pixel size: 29.24 μm x 26.88 μm
  - Hit-driven readout
  - Readout speed: 400 Mb/s - 1.2 Gb/s
  - Power consumption proportional to the occupancy


![block diagram of the ALIPIDE pixel](image)

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EPICAL-2
(Electromagnetic Pixel CALorimeter prototype-2)

- New digital pixel calorimeter prototype
  - small digital calorimeter (3x3 cm$^2$ cross section)
  - 24 layers with each
    - 2 ALPIDE CMOS MAPS
    - 3 mm W absorber

- Project goal:
  - prove that the ALPIDE is suitable for a calorimeter
  - demonstrate suitability of ALPIDE as solution for FoCal high-granularity layers
    - two-shower separation under high particle density environment

R&D for the ALICE-FoCal detector proposal
Current work performed in the context of the Bergen pCT collaboration
Data Taking Setup

Cosmic muons
- ~6 months in 2020 at Utrecht University
- non-showering, well-defined track
- uniform energy deposition over all layers
- total ~9000 events

→ alignment, calibration
Data Taking Setup

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- **Electron Test Beam**
  - February 2020 at DESY TB22
  - electron (positron) beam
  - beam energies: 1.0, 2.0, 3.0, 4.0, 5.0 and 5.8 GeV
  - detector temperatures: 20°C, 25°C and 30°C
  - total: ~44 million events

  → energy linearity, energy resolution, shower profiles
Analysis Setup

- **Pixel masking**
  - noisy and dead pixel removal
  - chip classification from serial testing
  - pedestal runs
  - beam runs

- **Clustering**
  - pixel hits → cluster
  - DBSCAN algorithm
  - cluster comprised of adjacent hit pixels (eight neighbors)

- **Event selection**
  - single particles
  - minimal lateral leakage
Chip Alignment

✔ longitudinal position fixed
✔ three parameters for lateral position
  ▶ parallel shift: Δx, Δy
  ▶ rotation around z-axis: Δθ
✔ 3D track fitting + χ² minimization approach

→ alignment precision better than 10 µm

residual = cluster position - track fit
Chip Alignment

- longitudinal position fixed
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\( \rightarrow \) alignment precision better than 10 \( \mu \text{m} \)

residual = cluster position - track fit
**Beam Inclination**

- Beam direction is supposed to be parallel to the z-axis
- Correct tilt of the setup after cosmic alignment
  - Projecting hit positions in lateral plane
  - $(x^\text{hit} - x^\text{beam}) \text{ v.s. } (y^\text{hit} - y^\text{beam})$
- Deviation of $\Delta x$ and $\Delta y$ from 0 clearly indicates beam inclination

![Graph showing deviation of $\Delta x$ and $\Delta y$ from 0 for different beam energies/runs.](image)

![Diagram showing hit positions from injection point (5.8 GeV electron, layer 6).](image)

**Fit function**

$$f(x, y) = \frac{A}{r'} \cdot \exp\left(-\frac{r'}{B}\right)$$

$$r' = \sqrt{C + (x - x0)^2 + (y - y0)^2}$$

- 5 free parameters, A, B, C, x0 and y0
Energy Calibration

- assumption:
  - uniform energy deposition over all layers
  - average number of hits per chip
  - calibration parameter of chip responses

![Graph showing number of hits in layer 6 and average number of hits for EPICAL-2 preliminary data.](image)
Event Display

one-electron event
5 GeV
raw data

color coding: layers

detailed evolution of shower
Energy Measurement

- Total number of hits (clusters) per event
  - Gaussian shape with small asymmetry
  - Smaller width for clusters
  - Residual pileup at higher energy side
  - Low-energy contamination of beam
- Current study uses numerical mean and standard deviation
**Energy Linearity**

- numerical mean ($\mu$) from distributions of total number of hits (clusters)
  - clear energy dependence
  - similar performance between hits and clusters
  - small deviation from linearity, possibly caused by
    - cluster overlap
    - lower-energy contamination
    - energy leakage

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**Graph:**

- **Top Graph:**
  - Distribution of total number of hits (clusters)
  - 6 energy levels: 1 GeV, 2 GeV, 3 GeV, 4 GeV, 5 GeV, 5.8 GeV
  - Vertical axis: $N/N_0$ (normalized counts)
  - Horizontal axis: pixel hits in event

- **Bottom Graph:**
  - Energy dependence of mean ($\mu$)
  - Linear fit
  - Data points and fitted line
  - Energy range: 1 GeV to 6 GeV
Energy Resolution

- standard deviation (σ) / mean (μ)
  - better than EPICAL-1 (MIMOSA)
    JINST 13 (2018) P01014
  - close to analog SiW ECAL (CALICE)
    physics prototype
    NIM A608 (2009) 372

- better performance for clusters compared to hits
  - large cluster-size fluctuation
  - vertically directed tracks creating large cluster
  - calibration can be improved

→ energy resolution superior compared to previous prototype
Longitudinal Energy Profile

- reasonable description by gamma distribution
- peak position \( t_{\text{max}} \) proportional to \( \log(E) \)
  - \( t_{\text{max}}^{\text{Hit}} > t_{\text{max}}^{\text{Cluster}} \)?
  - more accurate calibration for the conclusion

\[ \text{work in progress} \]

→ first step in detailed shower shape analyses
Summary

- **Successful test of full digital pixel calorimeter (EPICAL-2)**
  - test with cosmic muons and electron beam (1.0~5.8 GeV/c)
  - ALPIDE sensor (high granularity CMOS MAPS) suitable for calorimeter use

- **EPICAL-2 performance at DESY TB**
  - preliminary energy linearity check
  - energy resolution improved compared to EPICAL-1
  - reasonable longitudinal shower shape

- **Outlook**
  - detailed study of shower development
  - evaluation of two-shower separation capability
  - further studies of high-energy behaviour (simulation and SPS test beam)
Contributors

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