Novel algorithms for a compact electromagnetic calorimeter alignement

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contributing to the activities of the FCAL-LUXE and DRDCalo

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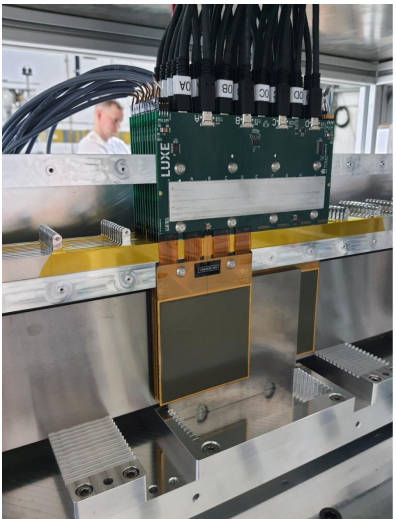
November 12, 2026
International Workshop on Future Linear Colliders
LCWS 2026

Beam tests of LUXE ECAL-P prototype

LUXE positron calorimeter design and prototype performance already discussed in details by previous speakers.

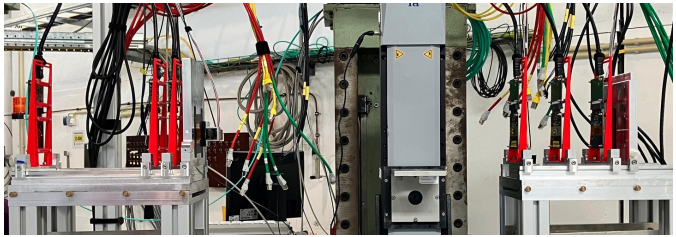
2025 Prototype @ DESY test beam:

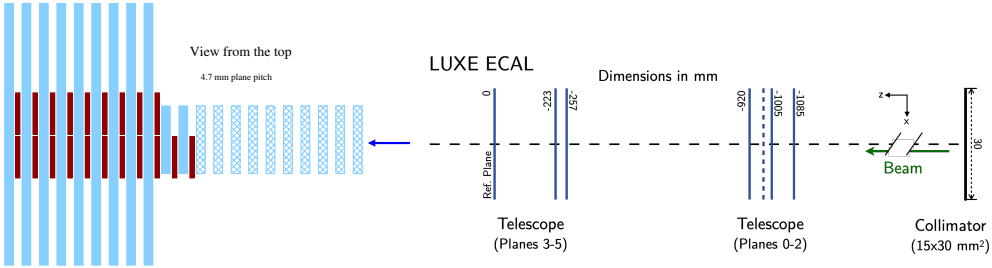
- final mechanical structure, but with sensor gap between the tungsten plates of 1.2 mm (1,0 mm for final design)
- two instrumented towers, with 11 and 9 planes respectively.
- Two running configurations
  - Calorimeter mode (deafult; sensors placed in gaps between 1 X_0 tungsten plates)
  - Tracker mode (sensors only, without tungsten plates, data dedicated to sensor performance studies)



ALPIDE telescope @ DESY Test Beam

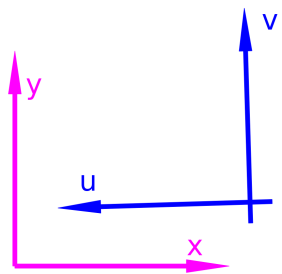
- Consists of six planes with sensor size 15 mm x 30 mm.
- Allows for precise particle position determination.





Telescope - Calorimeter alignment

Concept



We need to transform track position (x,y) in the **telescope reference frame** to position (u,v) in the **calorimeter frame**

(u,v) correspond to integer cell column and row numbers

General form of transformation:

$$\begin{aligned} u &= -a_x\,(\;x\cos\phi + y\sin\phi) + u_0 \\ v &= \;\;\;a_y\,(-x\sin\phi + y\cos\phi) + v_0 \end{aligned}$$

note horizontal coordinate sign flip

Main transformation parameters: u_0, v_0 and ϕ

Parameters a_x and a_y should correspond to sensor cell pitch

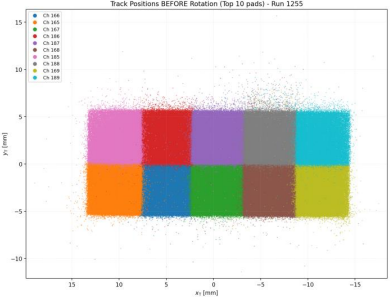
This the most basic transformation for single sensor

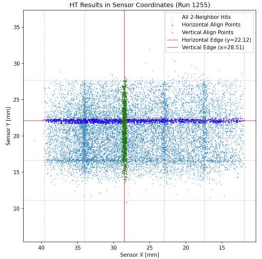
it has later been extended to global fit also including the z position and all the rotations.

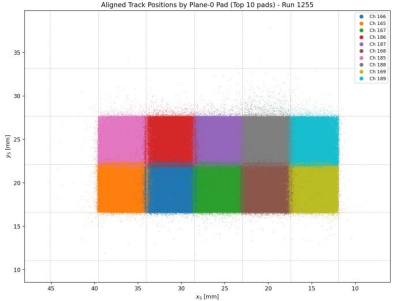
Edge alignment method

With $5.5 \times 5.5\,\mathrm{mm}^2$ readout pads, very coarse position information is obtained from calorimeter.
We constrain it much better if signal of single electron is observed in two neighbouring cells.
$\Rightarrow$ **Hough transform** can be then used to reconstruct cell edge position in telescope frame.

Works very well for the first plane (in front of the calorimeter) but not for the deeper ones.







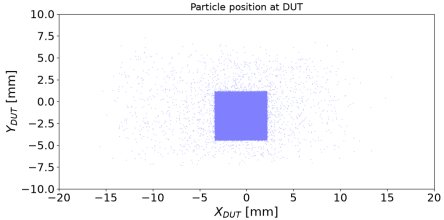
New alignment concept

New alignment concept is based on the observation that the core of the electromagnetic shower should follow the incident electron direction.

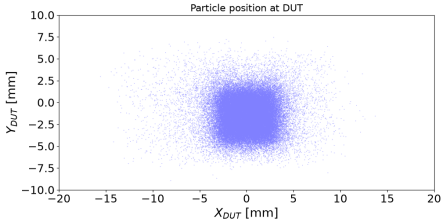
Even in deeper calorimeter layers, the maximum deposit is expected in the cell indicated by the extrapolated track.

This is clearly confirmed by the data: plots show incident track position from the telescope for events with maximum signal measured in a **specific cell**.

Sensor in front of the calorimeter

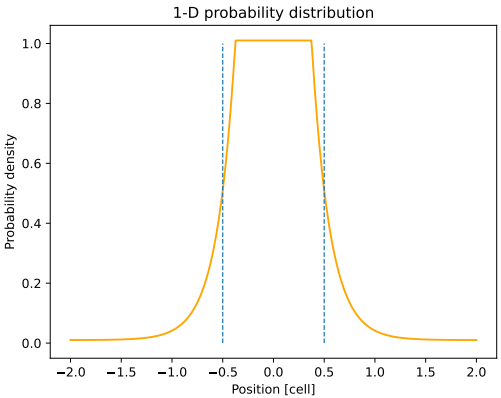


Sensor after 9 X_0 of tungsten



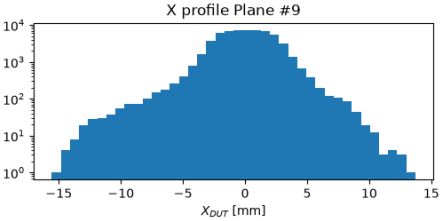
Likelihood function

Probability of given cell having maximum energy deposit in the considered layer



1-D parametrization:

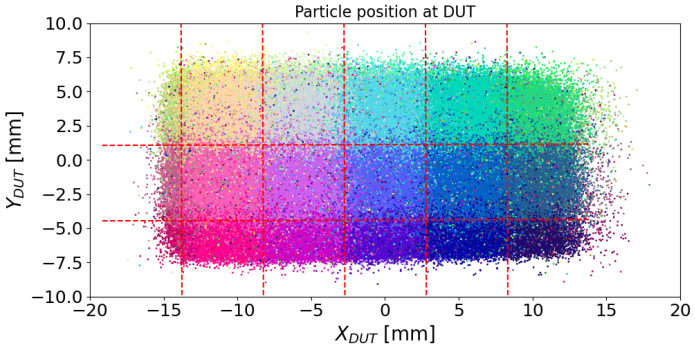
$$p(u, v) = \min\left(1, \frac{1}{2}\exp\left(-\frac{|u - i| - \frac{1}{2}}{\sigma_x}\right)\right)$$



Shower development ⇒ exponential tails become longer with calorimeter depth

Maximal Likelihood fit

Example fit for the calorimeter sensor plane after 9 X_0 of tungsten. Colors represent different cells.



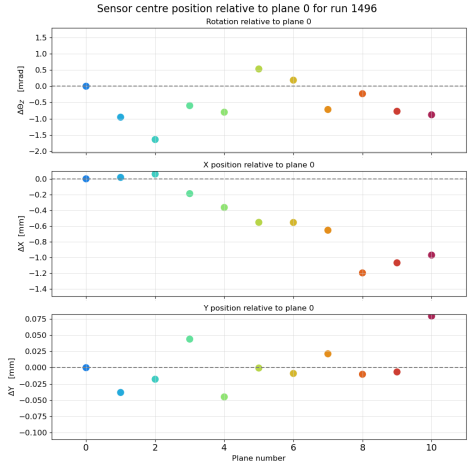
$$u_0 = 11.00265 \pm 0.00006$$

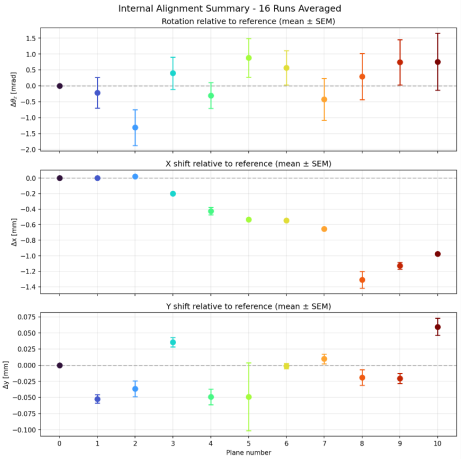
$$v_0 = 8.29796 \pm 0.00006$$

$$\phi = 0.00287 \pm 0.00011$$

With huge statistics of collected events (10^6 events per run), very precise positioning can be obtained for all calorimeter layers

Method comparison





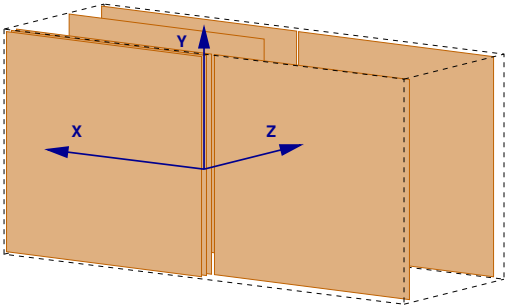
Likelihood fit (left) vs Hough transform (right) method comparison for tracker mode run(s)

Calorimeter geometry model

Prototype was placed on the movable table to allow for position (and angular) scan.
Position of each individual sensor could be reconstructed for each run...
However, calorimeter moves as a rigid body. Internal structure needs to be established once!

Then we only need to consider global transformation between the beam telescope and the calorimeter reference frame given by:

- position shift in three coordinates
- frame rotation around all three axis

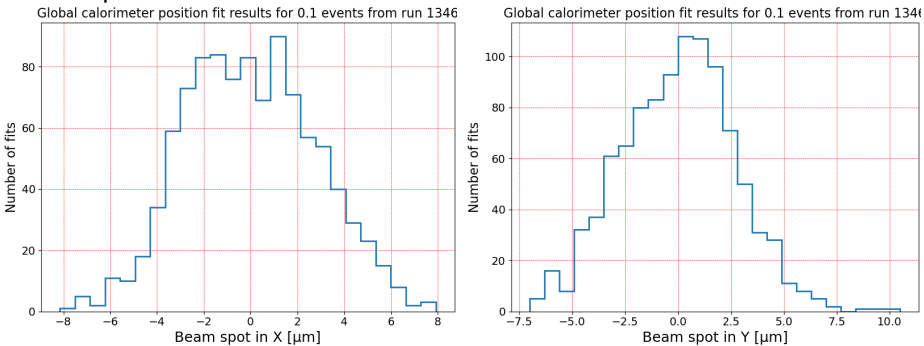


These **six parameters** need to be established **for each run** configuration !

Likelihood fit of global calorimeter position

With high statistics of events, calorimeter position can be very precisely established run by run. Statistical uncertainties estimated from fits to random subsamples of 100 000 events:

Nominal beam position on calorimeter face:



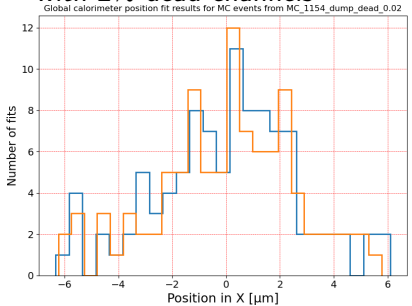
⇒ With 1 000 000 events, position can be determined with micrometer level precision

Systematic effects

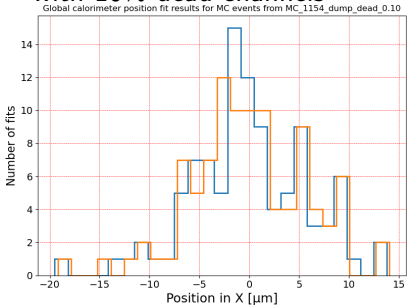
Impact of systematic effects on the global alignment precision has been studied with the detailed test setup Monte Carlo simulation samples.

Example: global position shift from (randomly selected) dead readout channels

with 2% dead channels



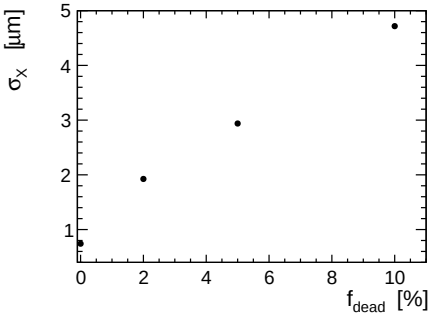
with 10% dead channels

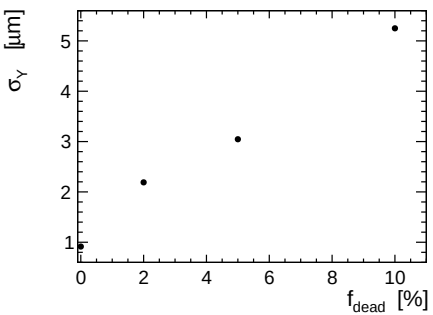


Systematic effects

Impact of systematic effects on the global alignment precision has been studied with the detailed test setup Monte Carlo simulation samples.

Impact of the **fraction of dead channels** on the global position uncertainty

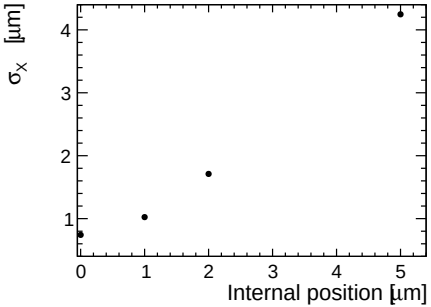


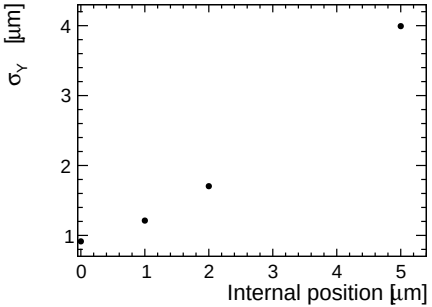


Systematic effects

Impact of systematic effects on the global alignment precision has been studied with the detailed test setup Monte Carlo simulation samples.

Impact of the **internal sensor positioning precision** on the global position uncertainty

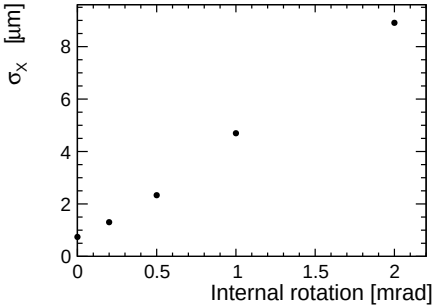


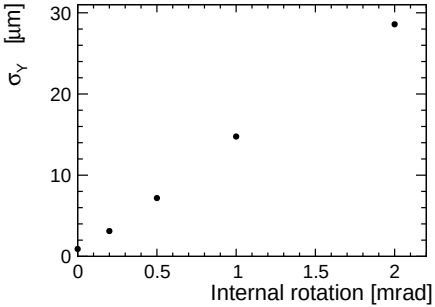


Systematic effects

Impact of systematic effects on the global alignment precision has been studied with the detailed test setup Monte Carlo simulation samples.

Impact of the **internal sensor orientation precision** on the global position uncertainty



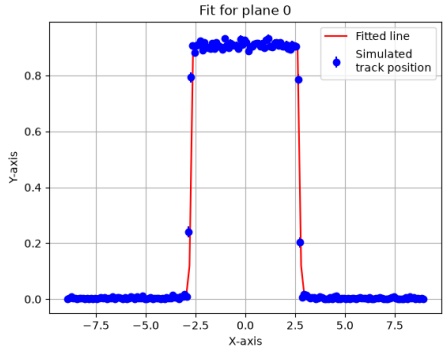


Likelihood alignment

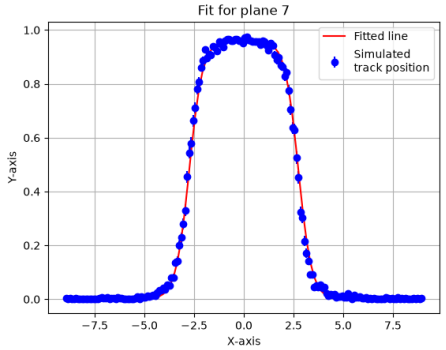
Work in progress: developing more precise cell response profiles based on Monte Carlo.

Example profiles:

front layer



after 7 X_0



Summary

- Proper alignment of the calorimeter with the beam telescope is crucial for precise calorimeter response studies.
- With high statistics of collected data μm level alignment of front sensor layers possible with both Hough transform and likelihood methods
- Likelihood method allows also for precise positioning of sensors inside the calorimeter, as well as for global calorimeter positioning.
- To reach μm level precision of global calorimeter alignment:
  - fraction of dead cells have to be below 1% level
  - sensor positions inside the calorimeter need to be known at μm level
  - sensor tilt need to be controlled below 0.1 mrad level
- The method could be applied for data-based positioning of luminosity detectors at future e^+e^- collider

Thank you for your attention!

Questions?

Calorimeter geometry model

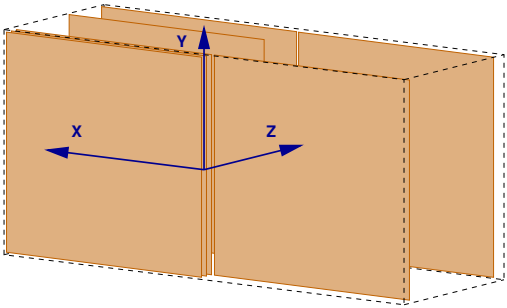
Dedicated framework was developed to describe alignment of all calorimeter sensors

We first consider alignment of a global ("ideal") calorimeter reference frame.

General transformation of track position and direction measured in the beam telescope to the calorimeter reference frame.

Implemented in two steps:

- position shift
  in three coordinates
- frame rotation
  around all three axis



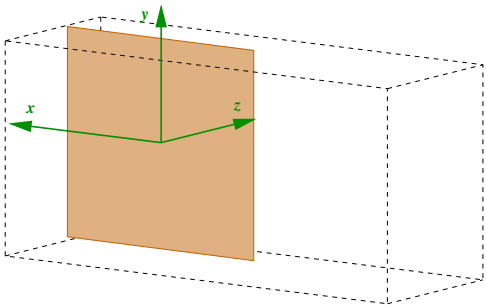
These **six parameters** need to be established **for each run** configuration !

Calorimeter geometry model

Second step is to transform track position and direction in the calorimeter frame, to its position in the reference frame of each sensor.

For each sensor we need to define:

- position of its center in the calorimeter
- its rotation angle



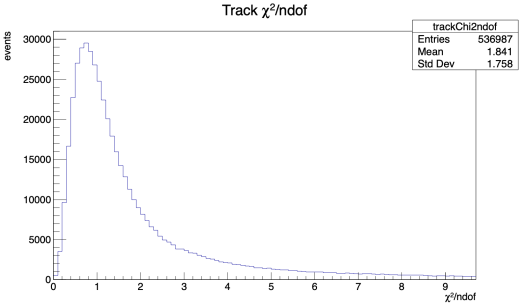
Only three parameters per sensor: x_0, y_0, Θ_Z

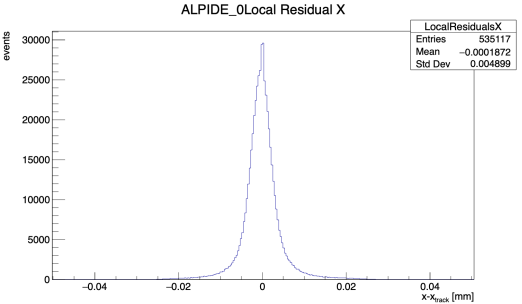
- position in Z taken from geometry,
- only rotation around Z axis possible

The three parameters need to be calculated only **once per detector configuration**!

New ALPIDE telescope

ALPIDE sensors (29x27μm^2 pixels) measure track position with precision down to 3 μm.
Six-plane track fit performed in `Corryvreckan` taking multiple scattering into account.





At 5 GeV, track position at the calorimeter face is reconstructed with about 40 μm precision.
Dominated by multiple scattering in the last sensor plane.