Test-beam measurements of instrumented sensor planes for a highly compact and granular electromagnetic calorimeter

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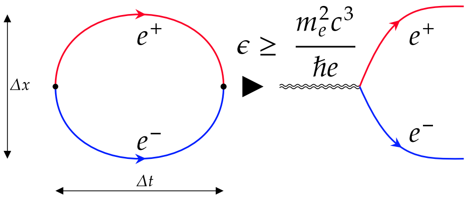
Plan of the presentation

1. LUXE experiment
2. ECAL-p calorimeter
3. Sensors
4. Readout electronics
5. Test-beam results of GaAs and Si sensors
   - 5.1 Cross-check with simulation
   - 5.2 Observation of signal sharing
   - 5.3 Homogeneity of detector response
6. Conclusions

QED in strong fields: SFQED

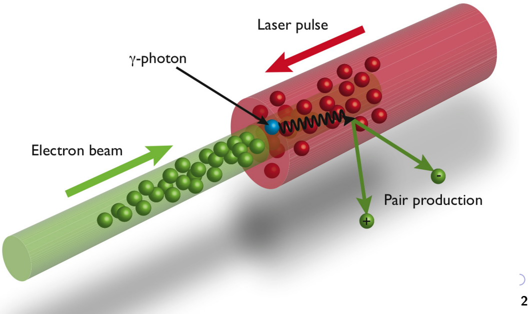
- For large values of EM field $\varepsilon \to$ the **Schwinger critical field** ε_{crit} is surpassed and the **vacuum becomes unstable** to pair production

$$\varepsilon_{crit} = \frac{m_e^2 c^3}{\hbar e} = 1.32 \times 10^{18}\,\frac{V}{m}$$



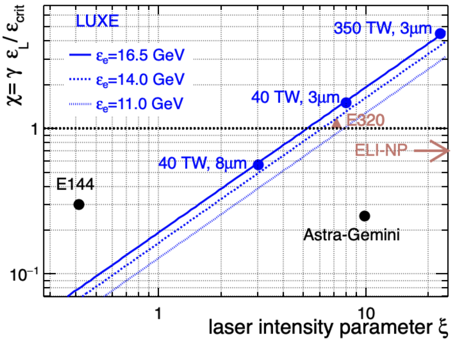
- **Perturbative QED breaks down** in the presence of strong fields

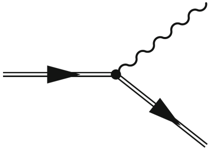
- **Such fields have not been reached experimentally** in laboratories although they are expected to exist:
  - on surface of neutron stars;
  - in bunches of future linear e^+e^- colliders.
- Can be reached by **colliding high intensity laser beams with a high-energy electron beam** but:
  - lasers powerful enough don't exist yet;
  - a high energy e^- beam is required: The EM field strength is boosted.



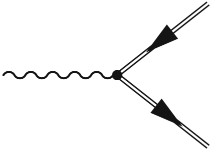
LUXE: Laser Und XFEL Experiment, physics motivation

- Experiment based at **DESY-XFEL**
- **Strong EM field**: 30-350 TW **laser** & 16.5 GeV **e$^-$ beam**
- **CDR** Eur. Phys. J. Spec. Top. 230, 2445–2560 - published
- **TDR** Eur. Phys. J. Spec. Top. arXiv:2308.00515 - accepted

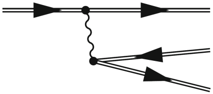




- **Non-linear Compton** $e^\pm \to e^\pm + \gamma$

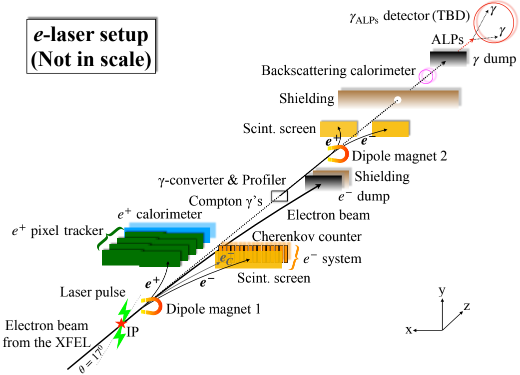


- **Non-linear Breit-Wheeler** $\gamma \to e^- e^+$

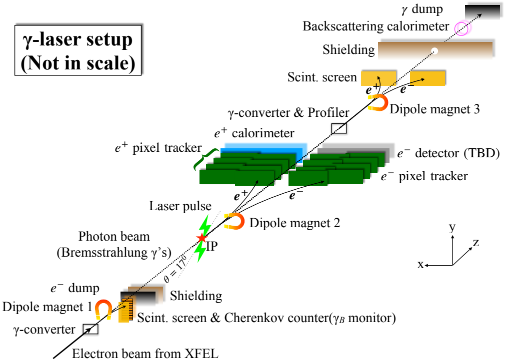


- **Non-linear trident** $e^\pm \to e^\pm + e^- e^+$

LUXE experiment - two possible setups



Electron laser setup



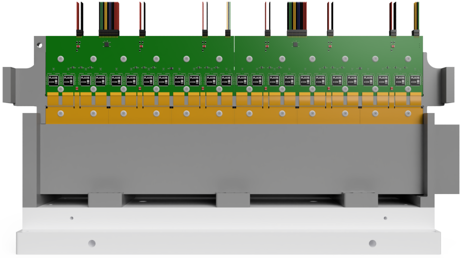
Gamma laser setup

ECAL-p calorimeter

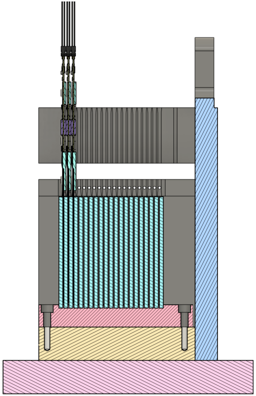
ECAL-p will be used to measure independently the number and the energy spectrum of positrons after each bunch crossing.

ECAL-p calorimeter

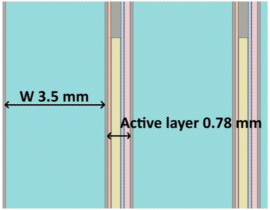
- 20 sandwich type layers
- 3.5 mm tungsten absorber
- $\sim$1 mm semiconductor sensor active layer



Stacked layers of calorimeter in positioning frame



Cross-section of calorimeter with 3 readout layers



Zoom on cross-section of two layers

Sensors

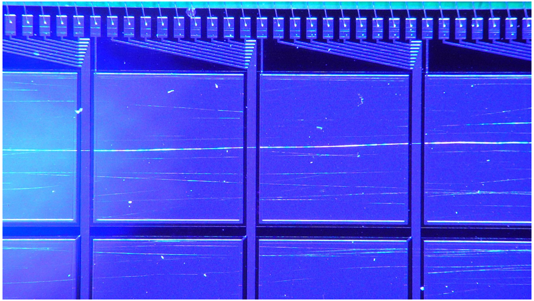
Two types of sensors are used in the test-beam.

Gallium Arsenide sensor:

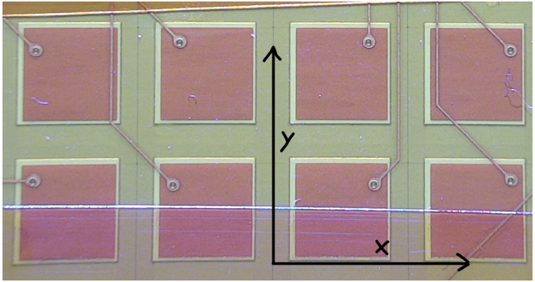
- National Research Tomsk State University
- array of 4.7 $\times$ 4.7 mm^2 with 0.3 mm gap between pads
- thickness 500 μm
- total area of 51.9 $\times$ 75.6 mm^2

Silicon sensor:

- produced by Hamamatsu
- array of 5.5 $\times$ 5.5 mm^2, $p+$ on n substrate diodes
- thickness 500 μm
- total area of 89.9 $\times$ 89.9 mm^2



Gallium Arsenide sensor **with traces** in the sensor

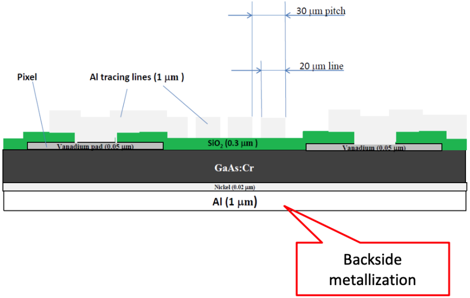


Silicon sensor **requires external fanout**

Sensors

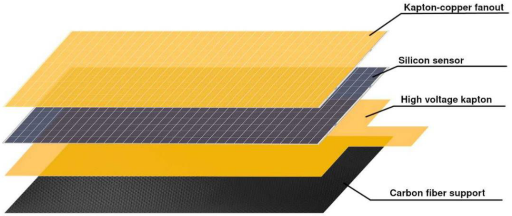
Two types of sensors are used in the test-beam.

Gallium Arsenide sensor:



Cross-profile of a GaAs sensor. The aluminium traces are positioned between the pads, on the top of the passivation layer

Silicon sensor:



Silicon sensor requires external fanout

FLAME front-end ASIC

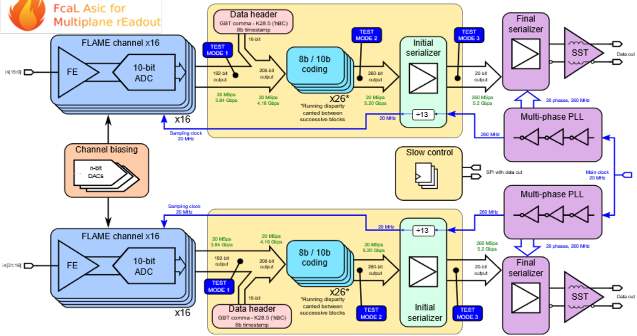
FLAME(**F**ca**L** **A**sic for **M**ultiplane r**E**adout) is a 32-channel ASIC in CMOS 130 nm with analog front-end and 10-bit ADC in each channel, followed by two fast (5.2 Gbps) serializers and data transmitters. FLAME has been already used in several test-beams of FCAL and LUXE-ECALp collaborations.

FLAME ASIC specification:

- Analog front-end in each channel
  - CR-RC shaping (T_{peak} ∼50 ns)
  - switched gain (high gain for MIPs, low gain for showers)
  - C_{in} 20-40 pF
- 10-bit ADC in each channel
  - $f_{sample} = 20$ MHz
  - ENOB > 9.5
  - Power $< 350\ \mu$W @ 20 MHz

The final version of the experiment will use a new front-end ASIC FLAXE, which is based on FLAME.

FLAME
FcaL Asic for Multiplane rEadout



Block diagram of a 32-channel FLAME ASIC

2022 Test-beam

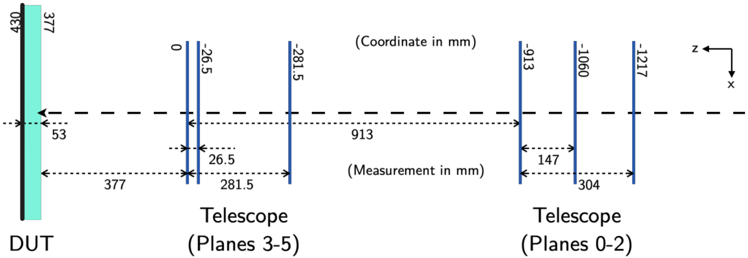
In September 2022, at the DESY Hamburg Facility, prototypes of calorimeter sensors where tested.

Test-beam data are used to measure:

- homogeneity of the sensor response,
- edge effects, response between pads.

In addition:

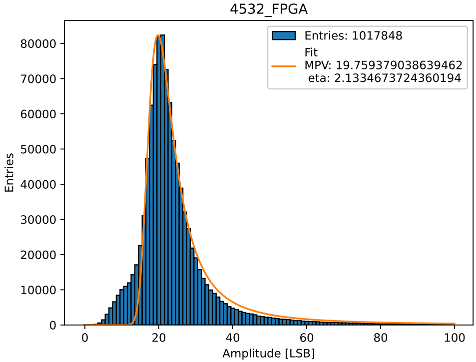
- comparison of the results of a simulation with data,
- test of the FPGA based data preprocessing.



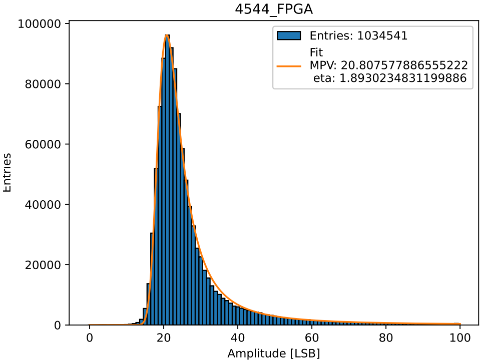
Scheme of the test beam set-up. Electrons arrive from the right, pass the first scintillator, then six Alpide pixel sensors, the second scintillator, and hit the sensor, denoted here as DUT (Detector under Test).

Examples of signal distribution

Examples of signal distributions obtained in a 5 GeV electron beam crossing the GaAs and silicon sensors. Fits are performed using a Landau distribution convoluted with a Gaussian. The peak value of the Landau distribution is denoted as "most probable value", MPV.



Signal distribution in a **GaAs sensor**

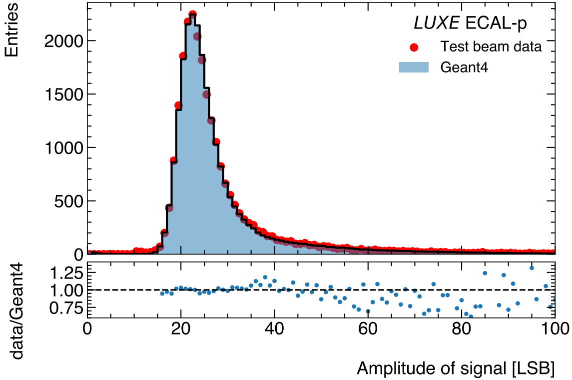


Signal distribution in a **silicon sensor**

Comparison of a simulation to the signal distribution in data for the silicon sensor

The distribution of the signal size, as measured in the test-beam, is compared to the results of the Geant4 simulation.

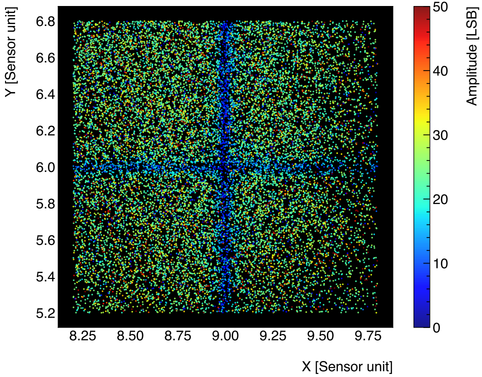
- The energy loss distribution of a **5 GeV** electron in a 500 μm thick silicon sensor is obtained from a **GEANT4** simulation
- the values of the energy loss are converted into charge carriers using 3.6 eV per electron-hole pair
- the gain of the read-out chain is determined feeding in a test charge to be **3.45** $\frac{LSB}{fC}$.
- treating the gain as a free parameter, a value of **3.46** $\frac{LSB}{fC}$ shifts the MPV value of the simulation to the one obtained in data



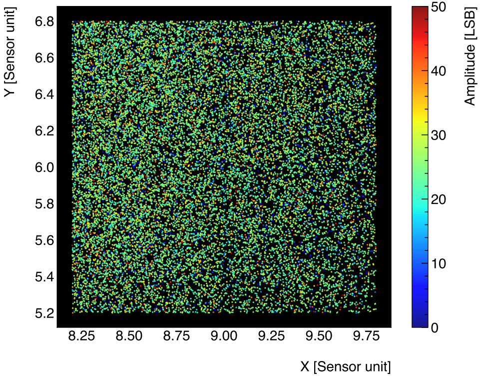
Distribution of the silicon sensor response to electrons from test beam data and MC simulations

Study of edge effects

After alignment with beam telescope spatial distributions of hits were studied for both sensors, in particular in region between the pads. Below is shown the population of impact points in a GaAs and silicon sensor. The colour indicates the size of the signals.



GaAs sensor - map of reconstructed particle position.

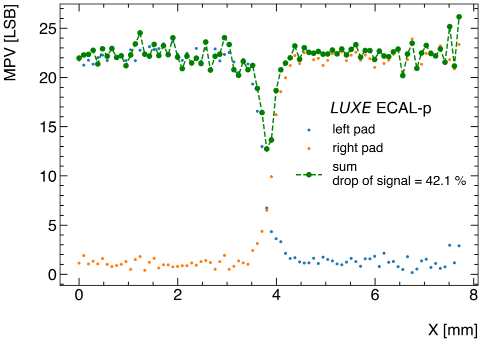


Silicon sensor - map of reconstructed particle position.

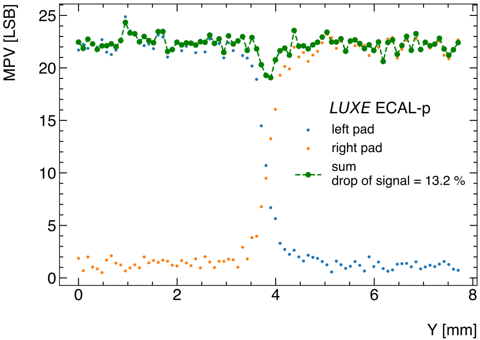
A clear loss of signal is seen for GaAs sensor in the region between pads.

GaAs sensor - edge effects - X scan vs Y scan

The MPV measured as a function of x and y, crossing the area between two pads. The sum of the MPVs as a function of x shows a drop of about **40%** in the region of the read-out strips. The same measurement as a function of y shows a drop of only roughly **15%**.



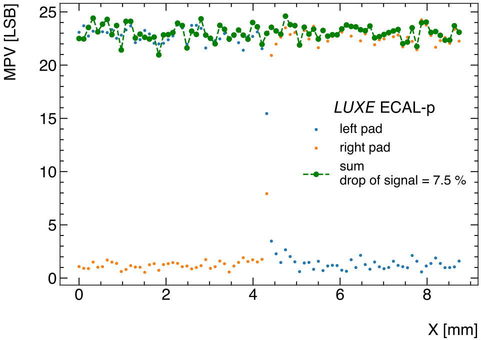
GaAs sensor amplitude data X scan - **traces between pads**



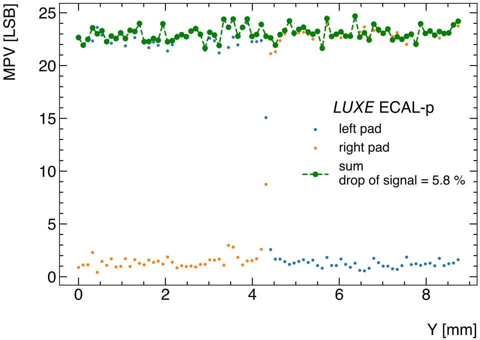
GaAs sensor amplitude data Y scan - **without traces between pads**

Silicon sensor - edge effects - X scan vs Y scan

The MPV measured as a function of x and y, crossing the area between two pads. No drop is observed in the sum of the MPVs



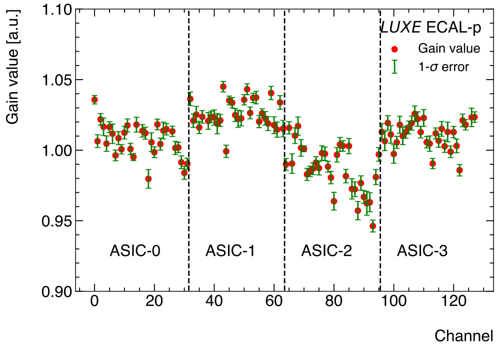
Silicon sensor amplitude data X scan



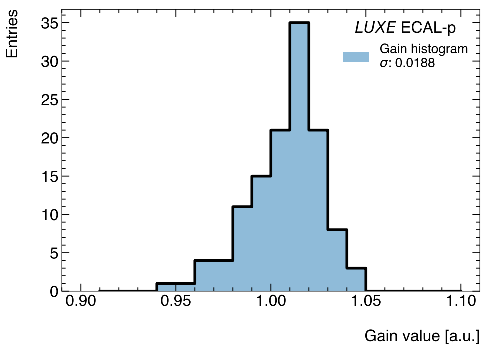
Silicon sensor amplitude data Y scan

Homogeneity of the Response

Homogeneity of the response may depends on several variables, in particular on gain of readout electronic channels. To determine gain values special charge injector was designed and calibrated.



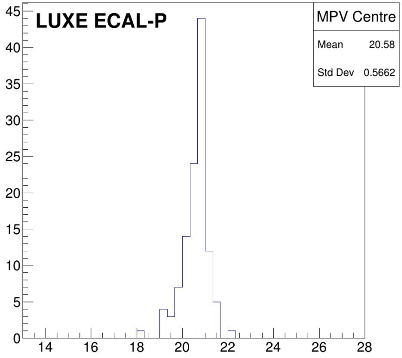
Relative gain values of all readout channels obtained from the charge injector.



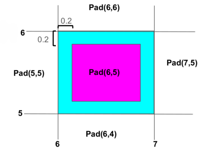
Histogram of relative gain values of all readout channels obtained from the charge injector.

Homogeneity of the Response

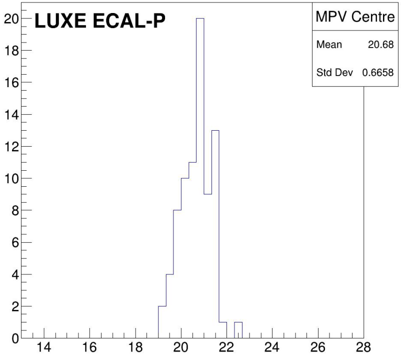
The MPV (most probable value) of the Landau-Gauss amplitude distribution for each channels was calculated, and gain correction was applied. The widths after gain corrections amount to 2.8 and 3.2 % for the GaAs and silicon sensors, respectively.



The distribution of the MPV values of all pads on the GaAs sensor.



Selected area of the sensor pad for MPV calculation



The distribution of the MPV values of all pads on the silicon sensor.

Conclusions

- Two prototypes of pad sensors considered for a highly compact and granular electromagnetic calorimeter are studied in a 5 GeV electron beam.
- The signal distribution is well described by a Landau distribution convoluted with a Gaussian.
- A simulation of the sensor response using the energy loss of 5 GeV electrons in silicon is in very good agreement with data converting the energy loss into charge and using the gain of the reaout chain.
- Calculated readout electronics absolute gain agrees between MC simulations and independent lab measurement.
- In GaAs sensor charge sharing is well visible and significantly depends on the traces which can cause 40 % drop of signal.
- In silicon sensor charge sharing is barely visible.
- The homogeneity of the response on all pads was measured after correction for different gains of the read-out channels. It amounts to 2.8 and 3.2 % for the GaAs and silicon sensors, respectively.

Thank you for attention