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

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**Abstract.** The LUXE experiment is designed to explore the strong-field QED regime in interactions of high-energy electrons from the European XFEL in a powerful laser field. One of the crucial aims of this experiment is to measure the production of electron-positron pairs as a function of the laser field strength where non-perturbative effects are expected to kick in above the Schwinger limit. For the positron energy measurements and multiplicity spectra, a tracker and an electromagnetic calorimeter are foreseen. Since the expected number of positrons varies over five orders of magnitude, and has to be measured over a widely spread low energy background, the calorimeter must be compact and finely segmented. The concept of a sandwich calorimeter made of tungsten absorber plates interspersed with thin sensor planes is developed. The sensor planes comprise a silicon pad sensor, flexible kapton printed circuit planes for bias voltage supply and signal transport to the sensor edge, all embedded in a carbon fibre support. The thickness of a sensor plane is less than 1 mm. As an alternative, gallium arsenide sensors are considered with integrated readout strips. Prototypes of both sensor planes were studied in an electron beam of 5 GeV at DESY. Results from this test beam are presented on the sensor response homogeneity, edge effects, signal sharing and embedded trace effect.

## 1 Introduction

Quantum Electrodynamics (QED) is one of the most well-tested theories in physics. The success of QED is based on comparing ultra-precise perturbative calculations with experimental data. However there exists a regime in which perturbative calculations of QED break down, namely in the vicinity of a strong background field. If the field energy is larger than the rest mass of a virtual particle, the vacuum becomes polarized. In strong-field QED this polarization is expected to manifest itself in the creation of physical electron-positron pairs from virtual electron-positron vacuum fluctuations. The critical field strength, $E_{crit}$, required for this process is called the Schwinger limit. The LUXE experiment [1] proposed at DESY and the European EU.XFEL in Hamburg and Schenefeld, Germany, is intended to study strong-field QED processes in collisions of a high-intensity optical laser and the 16.5 GeV electron beam of the EU.XFEL, as well as collisions of the high-intensity optical laser and high-energy secondary photons. The strong background field is provided by the Terawatt laser-pulse and

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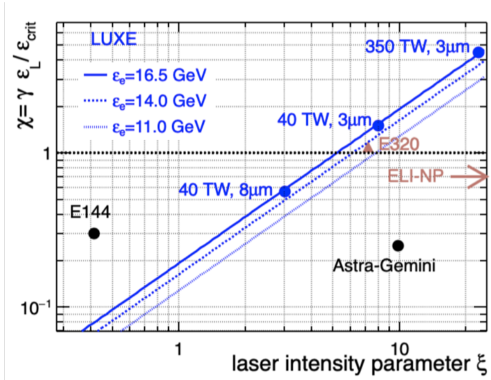



Figure 1: LUXE and strong-field QED experiments in the strong-field parameter space (E320 and ELI-NP are not yet operating). Two laser focus spot sizes are highlighted for the 40 TW (phase-0) laser and one for the 350 TW (phase-1) laser.

enhanced by the Lorentz boost of the electrons. This will allow LUXE to explore a previously uncharted intensity regime.

Two parameters are commonly used when describing processes of non-linear QED: the so-called classical non-linearity parameter of the laser field, $\xi$ that quantifies the coupling of the laser field to the probe charge. In the regime where $\xi \ll 1$, QED is fully perturbative, while, as $\xi$ approaches 1, an increasing number of higher-order processes contribute, until for $\xi > 1$, the perturbative expansion breaks down and QED becomes non-perturbative in the coupling to the laser field. The second parameter is the quantum parameter $\chi_e$ which, in case of electron-laser interaction, quantifies the ratio of the effective field strength in the electron rest frame and the critical field.

The main goal of the LUXE experiment is to measure the positron rate from vacuum polarization as a function of the laser intensity parameter $\xi$ and the quantum parameter $\chi$ and to compare it to theoretical predictions from strong-field QED.

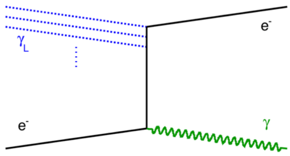
Figure 1 shows the region in parameter space that is accessible by the LUXE experiment, in comparison to a selection of past and future strong-field QED experiments. The $\chi$ and $\xi$ values accessible with LUXE depend on the power of the laser system as well as on the laser spot size. LUXE experiment will be able to go above the Schwinger limit ($\chi > 1$ and $\xi > 1$), already with a laser of 40TW (small spot size of 3 $\mu m$), the first planned stage of the experiment to be followed by a 350TW laser.

## 2 Positron production at LUXE

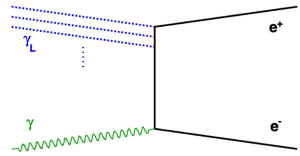
In electron-laser collisions, the processes of interest for the LUXE experiment are non-linear Compton scattering (see figure 2a) and subsequent non-linear Breit-Wheeler pair production (see figure 2b).

The numbers of electrons and positrons produced have been simulated and numbers are shown in figure 3. The positron rate varies between $10^{-1}$ to $10^4$ per bunch crossing.

To cope with this rate difference, the positron electromagnetic calorimeter (ECAL-P), based on the luminosity detector for future $e^+e^-$ collider[2], consists of a compact sampling calorimeter with a small Moliere radius and a high granularity [3]. It will consist of 20




(a) Non-linear Compton scattering.




(b) Non-linear Breit-Wheeler pair production.

Figure 2: Feynman diagrams of strong-field QED processes at LUXE.

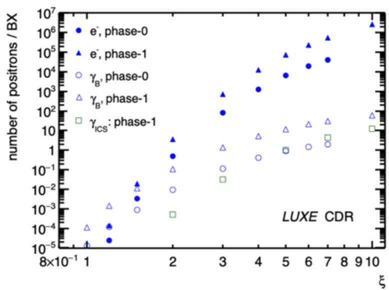



Figure 3: Number of positrons predicted by a MC simulation of non-linear Breit-Wheeler process. Different markers correspond to different sources of the initial photons (Bremstrahlung (B), Inverse Compton Scattering (ICS)).

tungsten layers (3.5 mm thickness = 1 $X_0$) with a 1mm gap in-between for the silicon active layers.

## 3 Test beam measurement of active planes

### 3.1 Sensors and setup

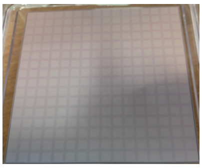
Two sensor materials, silicon and gallium arsenide (GaAs), were tested in a campaign in September 2022 at the DESY-II Synchrotron using a 5 GeV electron beam. The beam test aimed to study the sensor response and their performance as a calorimeter. This paper focus on the sensor response.

The silicon sensors are produced by Hamamatsu, they consist of 16 × 16 pads of 5.5×5.5 $mm^2$ and 500 $\mu$m thickness (figure 4a). They have been developed by the CALICE collaboration [4].

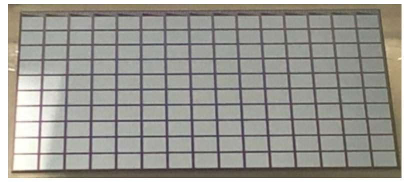
The GaAs sensors that were produced by the National Tomsk State University, have 15x10 pads of 4.7 × 4.7 $mm^2$ and 500 $\mu$m thickness (figure 4b). The distance between two pads is 300 $\mu$m whereas it is 10 $\mu$m for the silicon sensors.

To connect the silicon pad signal to the readout electronics, a kapton readout with copper traces (to the connector) is glued (with conductive glue to the sensor) (figure 5a).

For the GaAs sensors, 10 $\mu$m aluminium traces have been embedded in between the pads, connecting the pads to the top edge of the sensors (figure 5b), eliminating the need for a readout kapton.



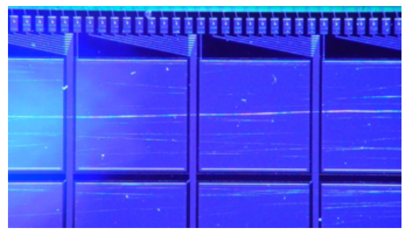
(a) Silicon sensor.



(b) GaAs sensor.

Figure 4: Sensors tested during the beam test at DESY.


(a) Sketch of instrumented silicon sensor.



(b) GaAs traces for the readout.

Figure 5: Sensor connections to the readout electronics.

The front-end ASIC for the readout of the sensor planes of ECAL-P is based on the FcaL Asic for Multiplane rEadout (FLAME), designed for the silicon sensors of the FCAL LumiCAL detector (32-channel ASIC, with a shaping time of 50ns followed by a 10-bit ADC). The FLAME ASICs have been used in several beam tests of the FCAL collaboration.

The geometry of the test beam setup is described in the figure 6. The electron beam passed

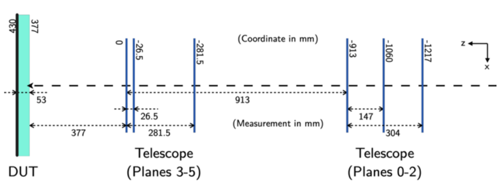
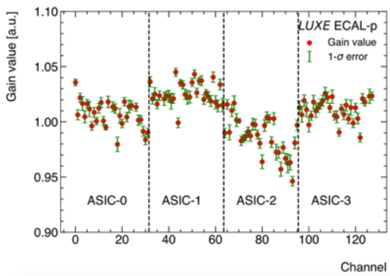



Figure 6: Geometry of the test beam setup. The DUT is one of the silicon/GaAs sensor.

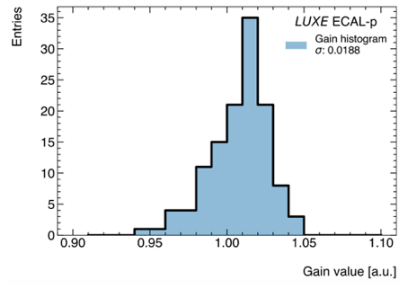
through a $12 \times 12\ mm^2$ square collimator that limits the beam spread along the test setup. The telescope is composed of six ALPIDE silicon planes [5], which provides a resolution of the extrapoled track of $\sim 35 \mu m$.

### 3.2 Calibration and simulation

In order to calibrate each front-end channels, a calibrated charge has been injected in all of the channels of the four ASICs, allowing a gain correction per channel (figure 7a). The figure 7b shows the distribution of the gain correction and presents a good homogeneity of the front-end preamplifiers.




(a) Relative gain vs channel number for four ASICs.




(b) Distribution of relative gains.

Figure 7: Front end calibration.

A simulation of the silicon sensor response to 5 GeV electrons has been compared to the data obtained in test beam, using the calibration of the preamplifier. Figure 8 shows a good agreement between data and simulated data for a MIP, around the most probable value (MPV).

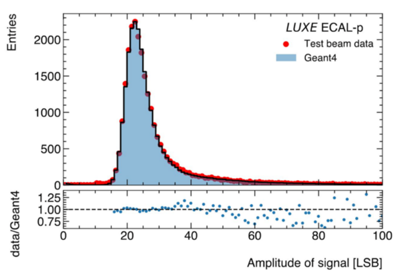


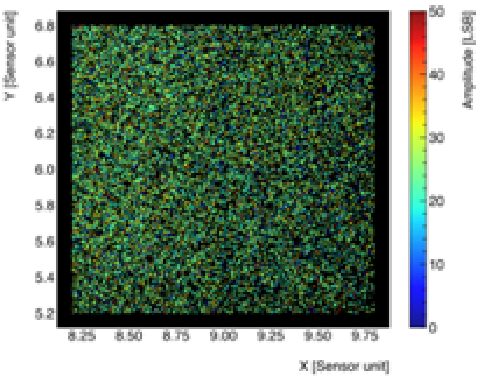

Figure 8: Comparison between calibrated data and simulated data for the silicon sensor.

### 3.3 Edge effects

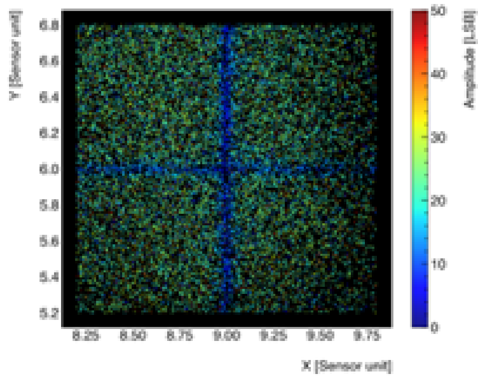
After the sensor alignment with the telescope, it was possible to extrapolate the position of each of the electrons on the sensors. Figures 9a and 9b show these hits as a function of the size of the signal for the silicon and GaAs sensors, respectively.

The loss of signal due to the 300 $\mu m$ gap between the GaAs sensor pads is clearly visible whereas it is barely observable for the silicon sensor (10 $\mu m$ between pads).

To quantify the edge effects, the pad area was divided into 100 thin strips. The MPV of the signal distribution of electrons hitting each strip area was calculated. The GaAs sensor shows a drop of 50% with respect to the center of the pad whereas the silicon sensor present a 3% drop (figures 10a and 10b). Since the beam was covering few pads, it was possible to study the signal sharing between two adjacent pads, in the x and y direction. Here again, an important drop of the signal size (40% and 15% respectively) is observed for the GaAs sensor in both spatial direction (figures 11b and 12b). Figures 11a and 12a show a continuous signal between two pads in x and y direction for the silicon sensor.

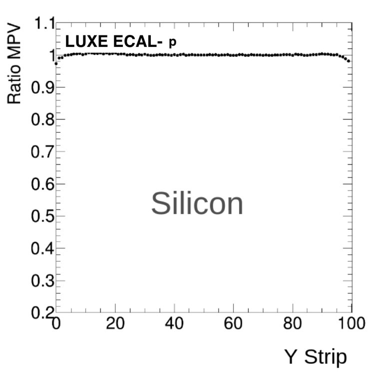



(a) Silicon sensor.

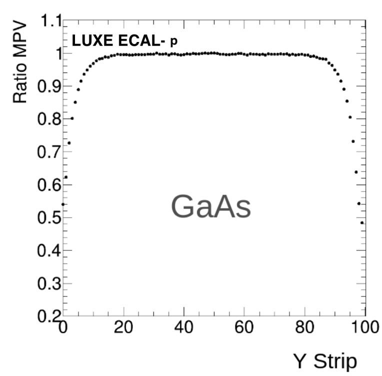



(b) GaAs sensor.

Figure 9: Hits distribution, extrapolated from the telescope, on the sensors.




(a) Silicon sensor.




(b) GaAs sensor.

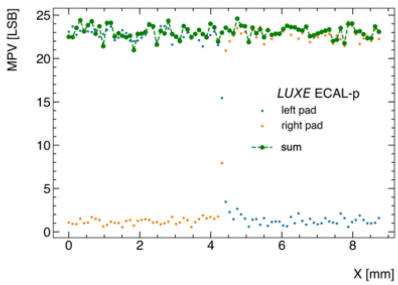
Figure 10: MPV in a pad normalized to the MPV of the center of the pad.

To perform a measurement of the signal distribution over all the pads of a sensor, the signal from electron hitting only the center of each pads was reported on figures 13a and 13b.

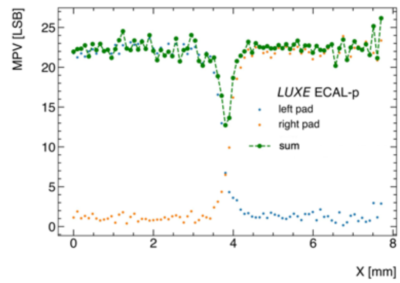
The homogeneity of the response of the GaAs sensor was found to be comparable to that of silicon after discarding electrons hitting the edges of pads. The homogeneity of the response in all pads is within 3% for both sensors.

### 3.4 Traces signal

A preliminary study started to measure the effect of electrons hitting the aluminum traces on the GaAs detector. To isolate the relevant hits, it was requested to get all the hits for a certain pad, but located outside this pad. Figure 14 shows the position of the electrons outside the pad of coordinates (8,4), but leaving signal in the pad. There are clearly two areas : hits around the pad which are due to the precision of the telescope, and hits along the trace (x=8). Figure 15a show the MPV of hits around the pads but very close to it and figure 15b shows

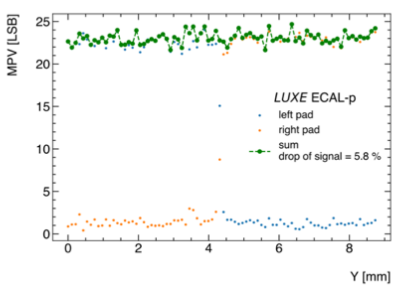



(a) silicon sensor.

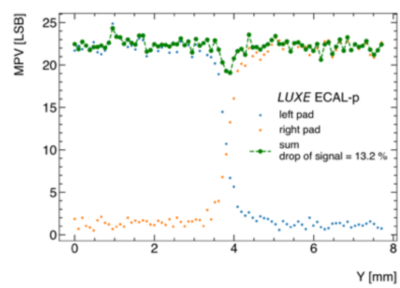



(b) GaAs sensor.

Figure 11: Response of the thin strip along x normalized to the MPV of central strip.




(a) silicon sensor.




(b) GaAs sensor.

Figure 12: Response of the thin strip along y normalized to the MPV of central strip.

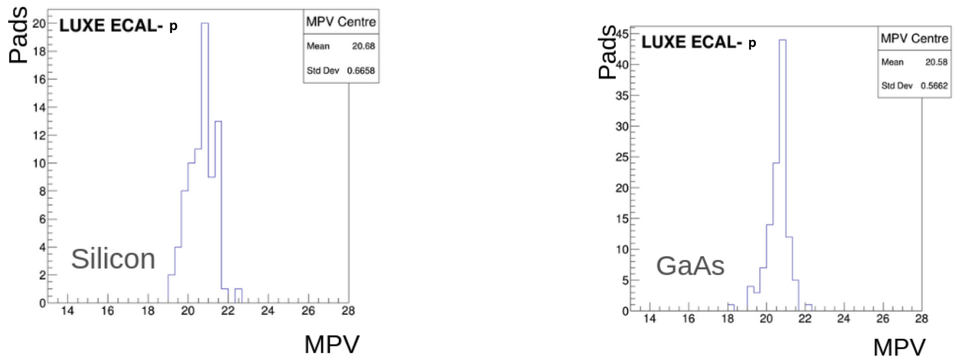
the MPV signal from hits along the trace. The traces are behaving like microstrips, producing signal from electrons interacting near by.

## 4 Conclusion

The LUXE experiment will explore the strong-field QED predictions using the European XFEL and a high power laser. All the detectors have been designed and tuned to cope with rate measurements, from $10^{-1}$ to $10^4$ per bunch crossing.

The ECAL-P collaboration, in charge of the positron electromagnetic calorimeter [1], tested two types of sensors (Si and GaAs) in a 5 GeV electron beam at DESY. After a readout calibration, the collected data are in good agreement with the simulated data. An important edge effect is observed for the GaAs sensors related to the 300 $\mu m$ gap between pads. Indeed, for the silicon where the gap is only 10 $\mu m$, there are almost no edge effects.

A preliminary study shows that readout traces embedded on GaAs sensors, are behaving like microstrips and detects electrons which is not an appropriate solution for this calorimeter.




(a) silicon sensor.

(b) GaAs sensor.

Figure 13: Distribution of the MPV for electrons hitting the center of the pads.

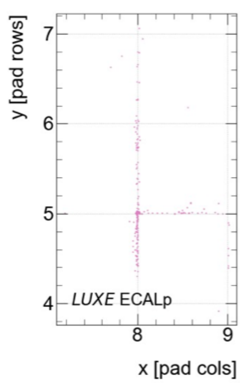



Figure 14: Electron hit position around the selected pad (units are in pad number).

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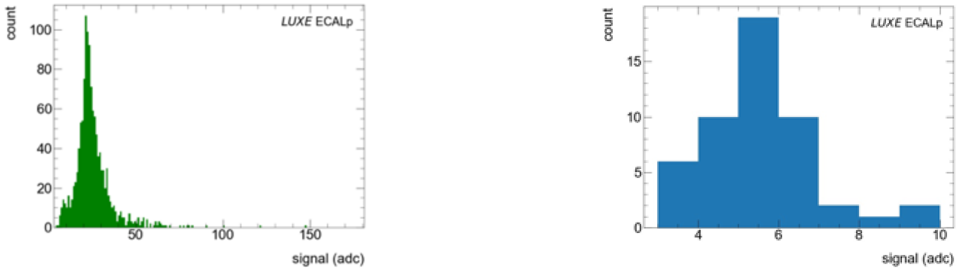


(a) Hits very close to the pad

(b) Hits along the trace

Figure 15: Distribution of the MPV for electrons hits outside the pad, leaving signal in the pad.