Instrumentation Challenges of the Strong-Field QED Experiment LUXE at the European XFEL

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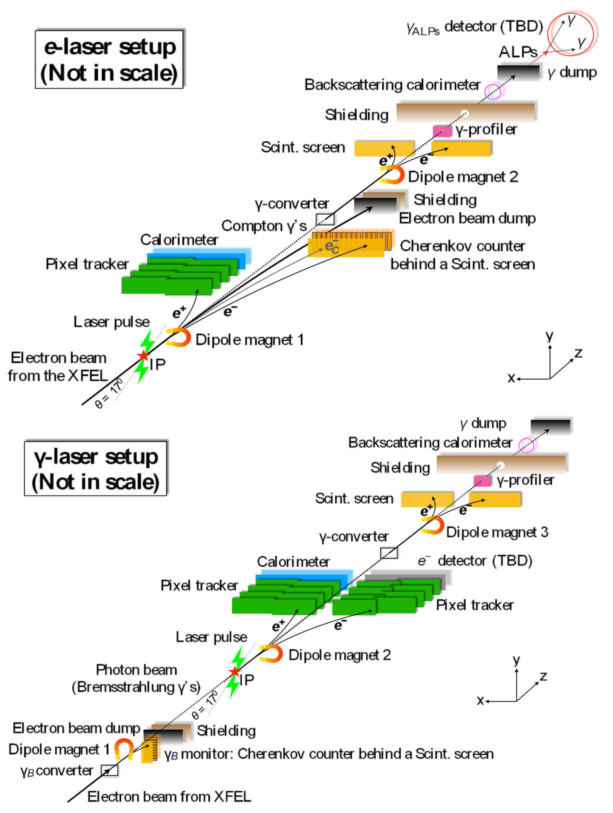
Abstract

The LUXE experiment aims at studying strong-field QED in electron-laser and photon-laser interactions, with the 16.5 GeV electron beam of the European XFEL and a laser beam with power of up to 350 TW. The strong-field QED processes are expected to have production rates ranging from 10^{-3} to 10^{9} per 1 Hz bunch crossing. Additionally, these measurements must be performed in a low-energy, high-radiation background. The LUXE experiment will utilise various detector technologies to overcome these challenges[1].

Map of the LUXE collaborators

Operating Modes



Expected Signal at LUXE

- The expected signal varies significantly across the experiment
- Background is generally lower energy across all detector systems although particle number may be higher
- Important that detectors can effectively reject the lower energy background

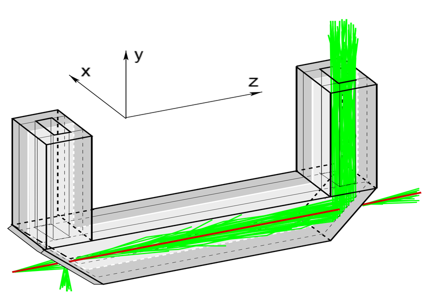
	Positron detection	Electron detection	Photon detection
Electron + laser	$\sim10^{-4}$ - 10^{7} $\sim10^{3}$ - 10^{4}	$\sim10^{6}$ – 10^{8} $\sim10^{4}$ - 10^{5}	$\sim10^{5}$ $\sim10^{3}$ - 10^{6}
Photon + laser	$\sim10^{-4}$ – 10 $\sim10^{2}$ - 10^{5}	$\sim10^{-4}$ – 10 $\sim10^{2}$ - 10^{5}	$\sim10^{5}$ $\sim10^{3}$ - 10^{6}

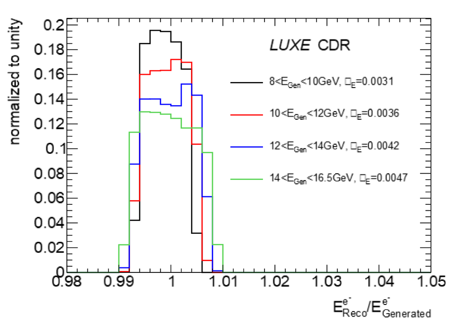
Table showing the expected signals (black) and background (red) per BX in each detector subsystem

Electron Detection

Čerenkov Detector

- Insensitive to low energy electrons/positrons and all photons[2]
- Resolution in reconstructing electron energy varies from 0.3 - 0.5%

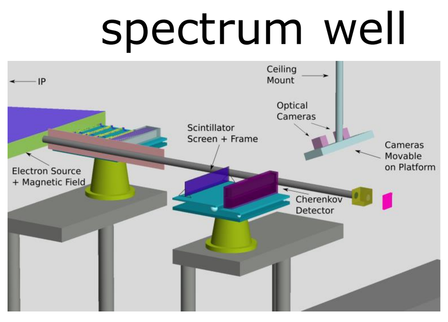




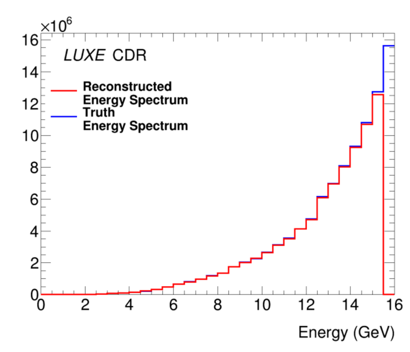
GEANT4 rendering of Čerenkov prototype (left) and reconstruction of electron energy (right)

Scintillator Detector

- Radiation hard with lower sensitivity to photons than electrons
- Reconstruction of electron spectrum from GEANT4 simulation accurate matches true spectrum well



GEANT4 rendering of the electron detection subsystem

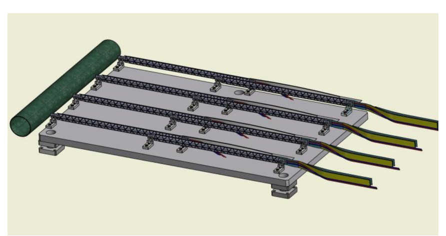


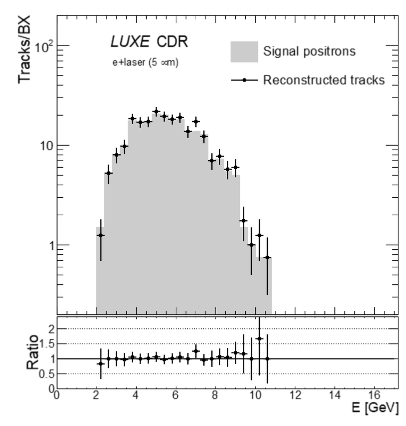
Reconstruction of electron spectrum from GEANT4 simulation

Positron Detection

Tracking Detector

- KF tracking algorithm[3] allows > 95% tracking for energies above 2.5 GeV
- Energy resolution ~0.27% from simulation
- In-situ resolution ~1%

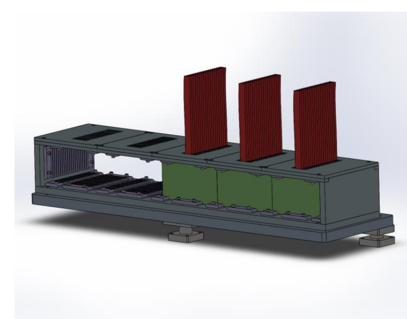




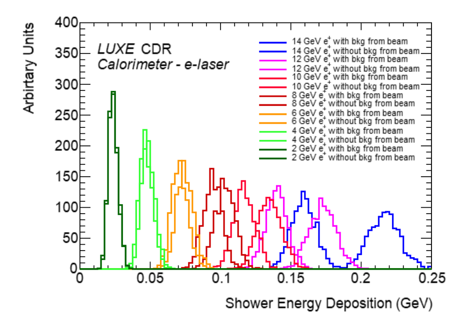
CAD model of tracker staves (above) and reconstruction of signal tracks (right)

Electromagnetic Calorimeter

- Provides high granularity for precise position measurements
- For both single electrons and positrons, resolution in energy ≲ 20%



CAD model of electromagnetic calorimeter

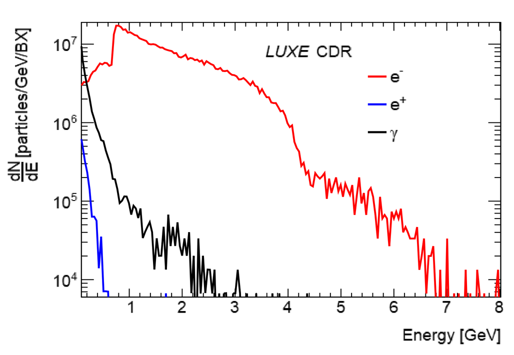


Total energy deposition in calorimeter

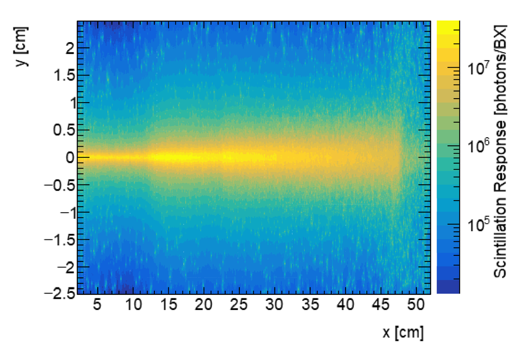
Photon Detection and Monitoring

Gamma Ray Spectrometer[4]

- From simulation studies, background photon flux ~10^{3} – 10^{4} particles/cm²/BX
- Background electron flux ~10 – 100 particles/cm²/BX
- Anticipated S/B > 10 - 100



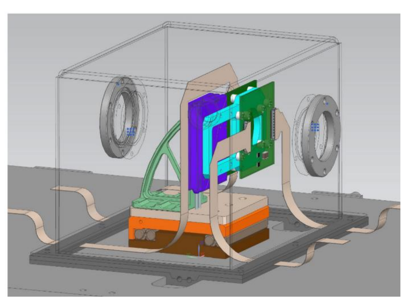
Simulated energy spectra at spectrometer scintillator plane



Simulated scintillator response (electron side)

Gamma Beam Profiler

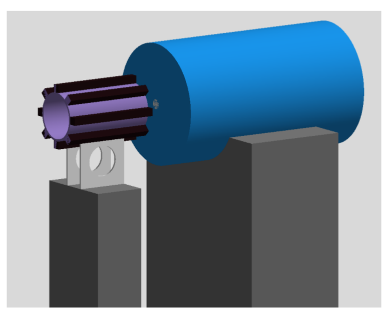
- Ideal precision of 5 μm in two orthogonal planes at profiler
- Sapphire has high radiation hardness; low leakage current and relatively small charge collection, 22 eh pairs/μm of MIP track
- Resolution scales with 1/√BX - 5 μm precision achieved after ~4 BX



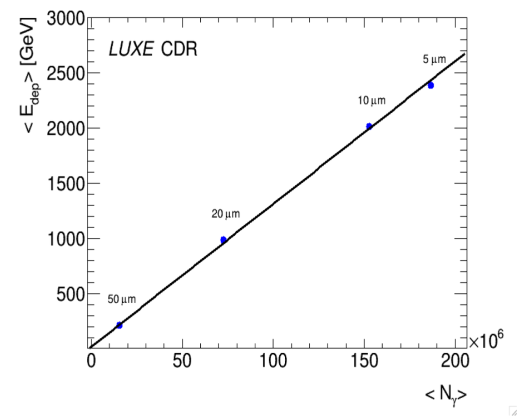
CAD model of current gamma profiler design

Gamma Flux Monitor

- Energy deposited directly proportional to mean number of photons entering GFM
- In-situ monitoring of crystal response
- Uncertainty in number of measured photons ~5 – 10%



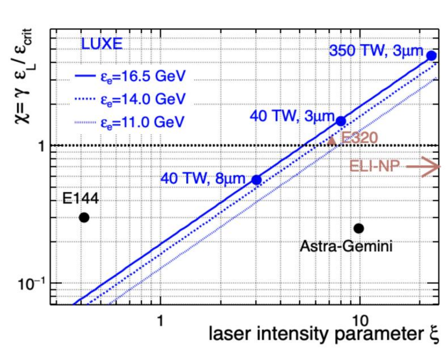
GEANT4 rendering of GFM



Simulated energy deposition in GFM

Conclusions

- At LUXE, expected signal varies over many orders of magnitude with a low-energy, high-radiation background
- Various detector systems have been proposed and their performance under LUXE conditions have been investigated
- Detectors have been developed to withstand high radiation levels as well as differentiate signal from low energy background
- Across all systems, a resolution of ≲ 15% is anticipated over the energy range of interest
- Many of the technologies developed can be adapted for use in other strong-field QED experiments



Parameter space under investigation at LUXE

References

[1]Abramowicz, H. et. al. (2021), "Conceptual Design Report for the LUXE Experiment," arXiv.2102.02032
[2]C. Bartels et al., "Design and Construction of a Cherenkov Detector for Compton Polarimetry at the ILC", JINST 7 (2012), P01019, arXiv:1011.6314.
[3]P. Billoir and S. Qian, "Simultaneous pattern recognition and track fitting by the Kalman filtering method", Nucl. Instrum. Methods in Phys Res A: Accel., Spectrom., Detect. and Assoc. Equip. 294 (1990), no. 1, 219, doi:https://doi.org/10.1016/0168-9002(90)91835-Y.
[4]K. Fleck, N. Cavanagh, and G. Sarri, "Conceptual Design of a High-flux Multi-GeV Gamma-ray Spectrometer", Sci. Rep.10 (2020) 9894, doi:https://doi.org/10.1038/s41598-020-66832-x.