Detector Challenges of the strong-field QED experiment LUXE at the European XFEL

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on behalf of LUXE

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Outline

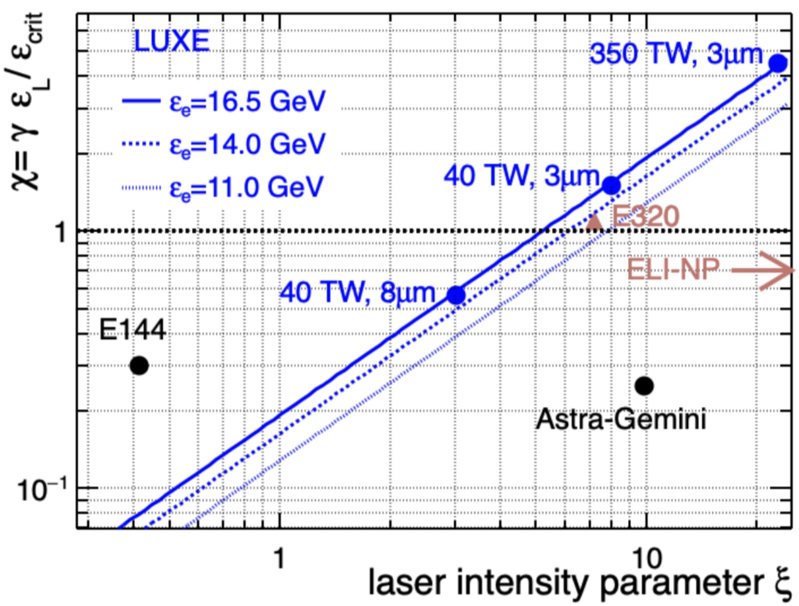
- Introduction
- LUXE physics observables
- Design of experimental setup at European XFEL
- Summary

LUXE experiment

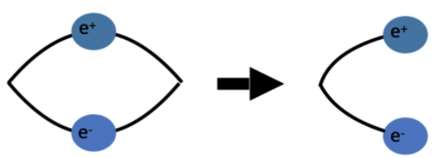
- new experiment proposed at DESY and Eu.XFEL
- collisions of XFEL electron beam and high-power LASER

Vacuum inside strong field

- QED: most well-tested theory in physics → based on perturbative calculations
- LUXE will study non-perturbative and non-linear QED phenomena in the strong-field regime



Vacuum boils if the field large enough to create real pairs:



$W_{field} < 2m_e$ $\quad$ $W_{field} > 2m_e$

$$W_{field} = \frac{\varepsilon e}{m_e}$$

$$\varepsilon_{crit} = \frac{m_e^2 c^3}{\hbar e} \simeq 1.3 \cdot 10^{18}\ \mathrm{V/m}$$

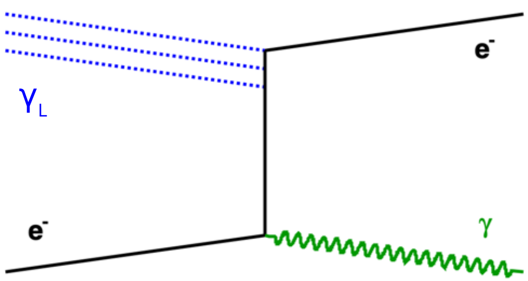
More on LUXE physics: Talk L. Helary, Talk N. Tal Hod

- LUXE CDR: arXiv:2102.02032
- LUXE website: https://luxe.desy.de

LUXE: Physics processes

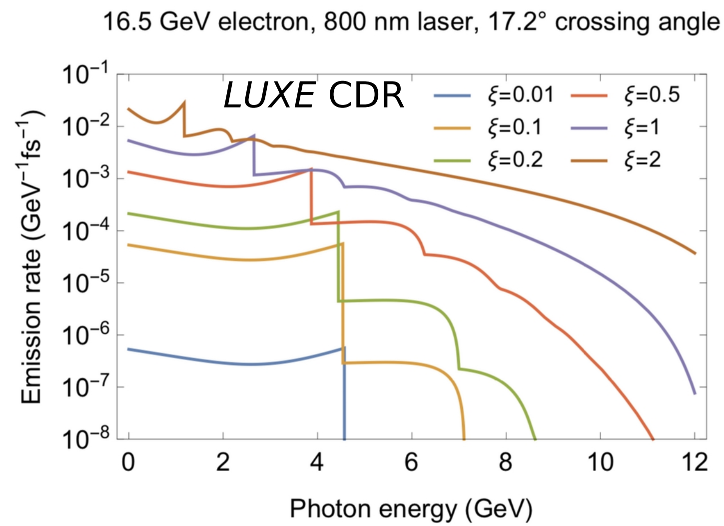
Non-linear Compton Scattering:

$$e^- + n\,\gamma_L \rightarrow e^- + \gamma$$



Observables:

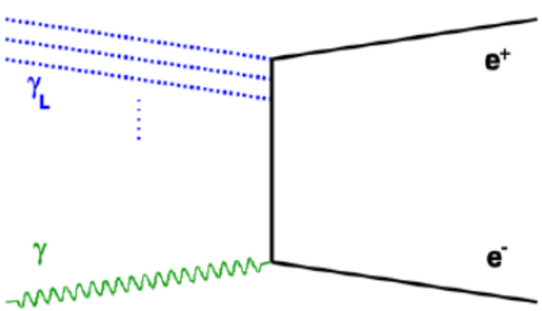
- Shift of first kinematic edge;
- Position of other kinematic edges;
- Intensity of nγ scattering.



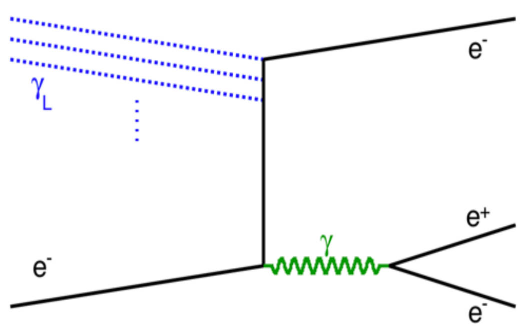
Pair production:

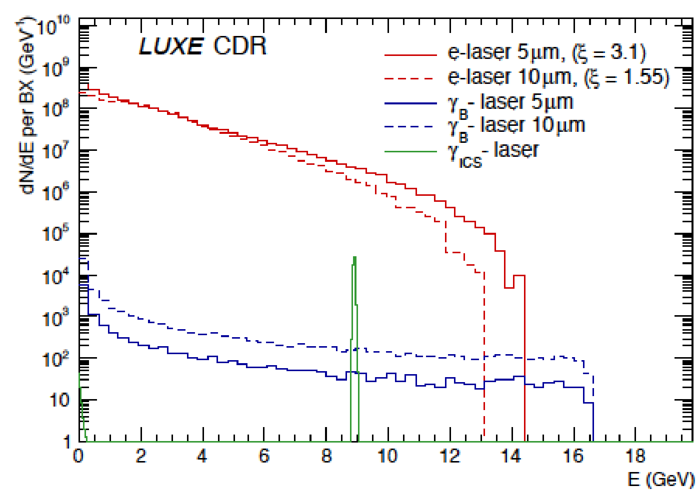
non-linear Breit-Wheeler and trident

$$\gamma + n\,\gamma_L \rightarrow e^+ + e^-$$



$$e^- + n\,\gamma_L \rightarrow e^- + e^+ + e^-$$





- Three methods for generating incident photon:
  - Compton photons inside same laser pulse => largest rate
  - Bremsstrahlung photons produced upstream => highest E
  - Inverse Compton scattering upstream (E=9 GeV)

Luxe setup

European XFEL electron beam:

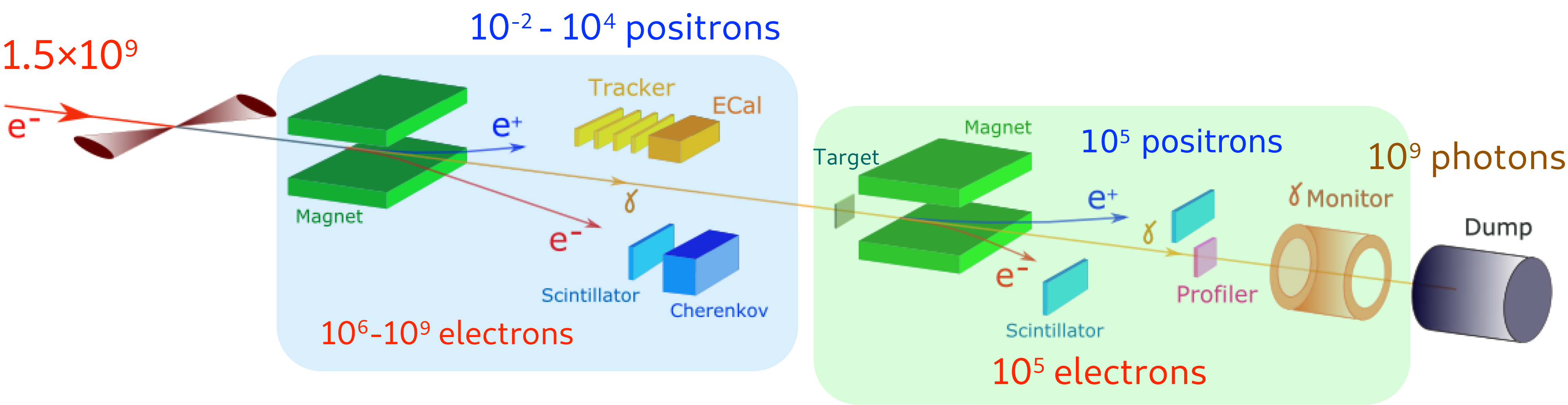
- Energy 16.5 GeV (possible 10 GeV, 14 GeV);
- Luxe uses one out of 2700 bunches per train;
- Repetition rate 10 Hz;
- Normalized emittance 1.4 mm mrad;

Laser:

- Laser wavelength = 800.00 nm (1.5498 eV);
- Repetition rate ~1 Hz;
- Power:
  - Phase 0: 40 TW, (1.3×10^{20} W/cm^2, $\xi = 7.9$);
  - Phase 1: 350 TW, (1.2×10^{21} W/cm^2, $\xi = 23.6$);

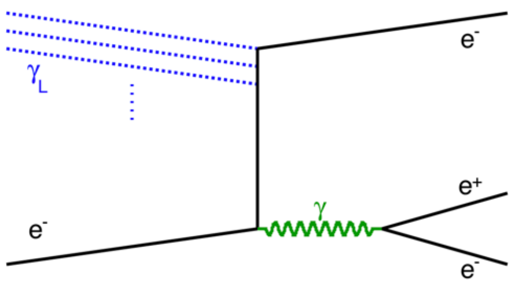
Luxe setup conceptually contains two detector subsystem:

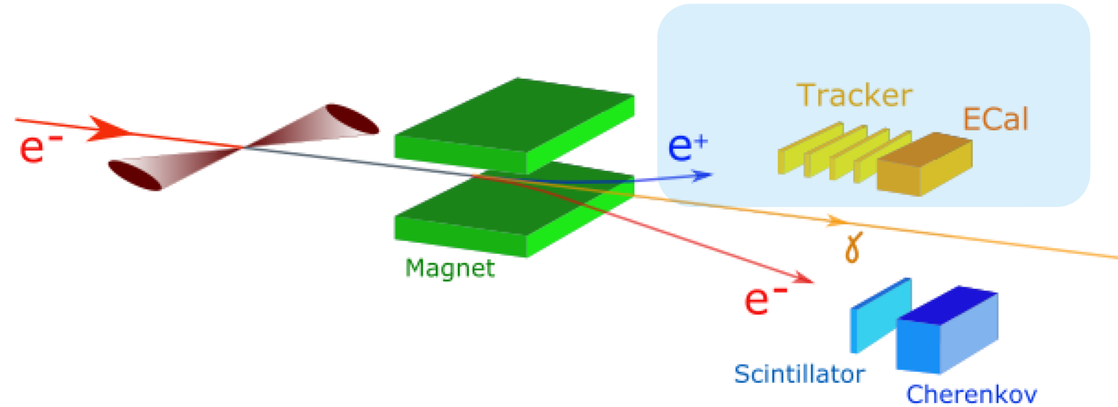
- Electron positron spectrometer
- Photon detection system



Positron Detection

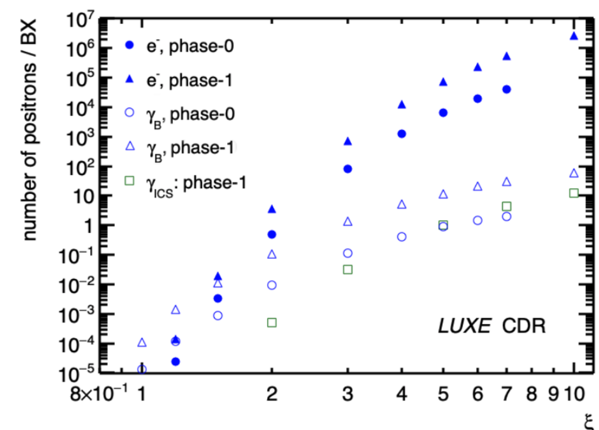
Study e+e- pair production





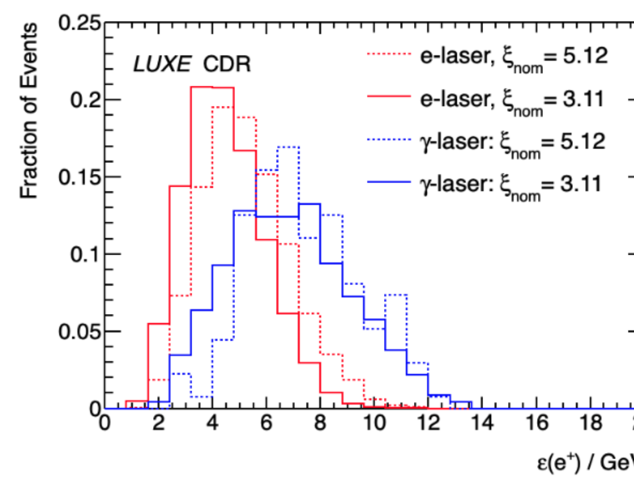
Expected event rates per laser shot

- electron-laser mode: 10^{-2}-10^{4} e^+e^- pairs
- gamma-laser mode: 10^{-2}-1 e^+e^- pairs

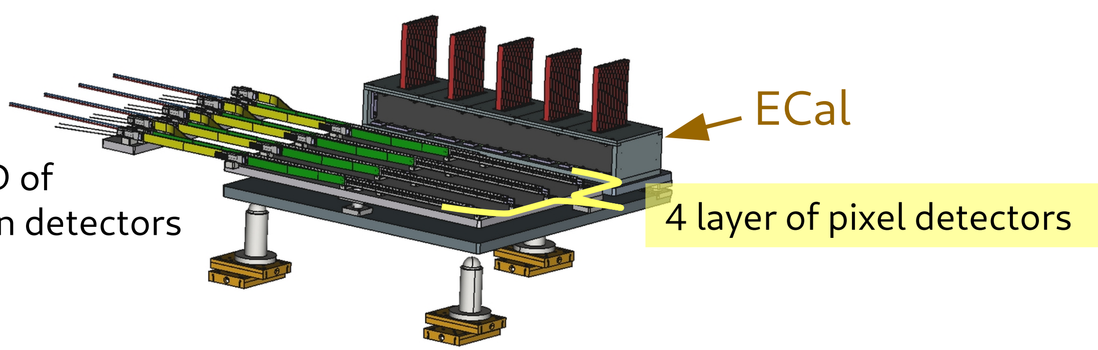


Spectrometer:

- Magnet: 1 T – 1.5 T of ~1 m;
- 4 layers of silicon pixel detectors
- Compact electromagnetic calorimeter

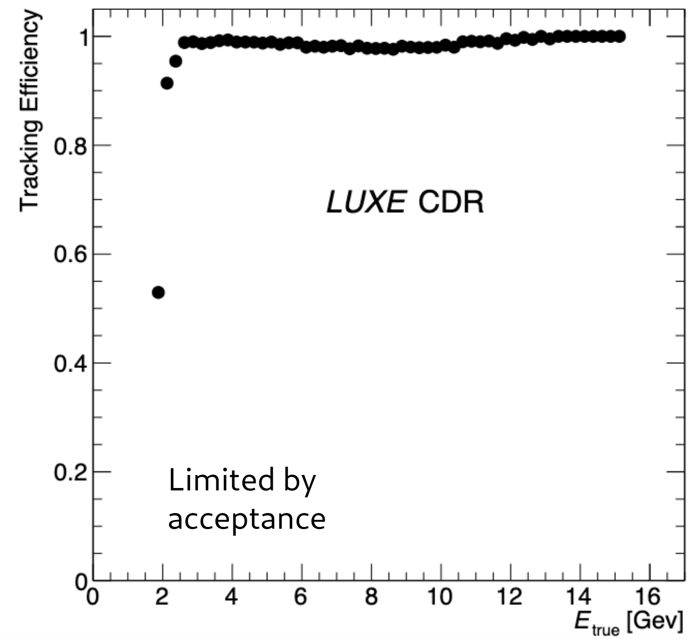


3D CAD of positron detectors



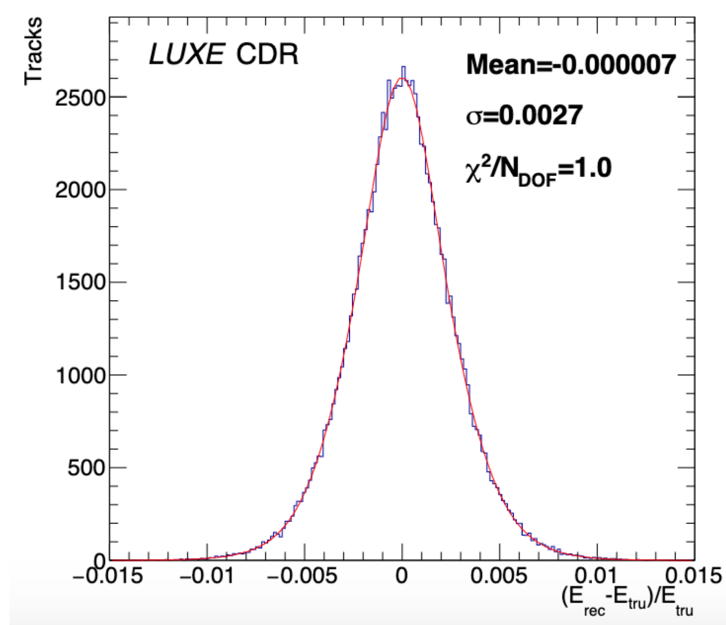
Tracker

- ALPIDE silicon pixel sensors: 15 x 30 mm^2;
- Sensors developed for upgrade of ALICE Inner Tracking System (ITS);
- Pixel size: 27 x 29 µm^2, spatial resolution ~5 µm;
- Good performance under irradiation - able to tolerate an ionization dose of up to 2.7 Mrad.



Performance in MC simulation

- Four layers of two ITS staves
- Energy resolution < 1%, independent of energy.
- Background: <0.1 particle per BX crossing

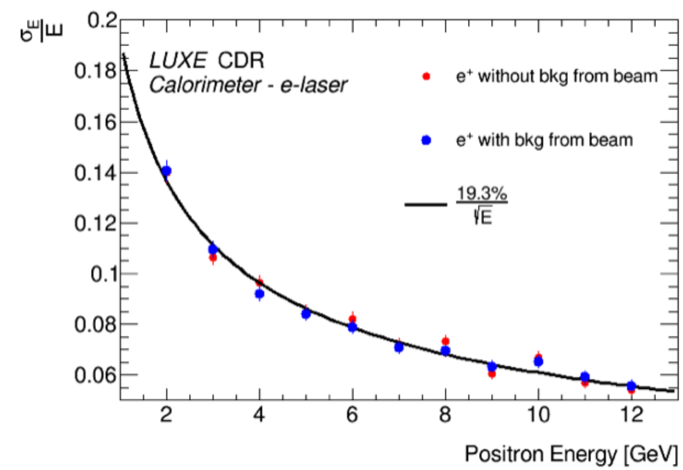


Electromagnetic Calorimeter

- Ultra compact ECal ~ 550 x 55 x 90 mm^3
- Developed by FCAL collaboration;
- Sampling calorimeter: 20 layers of 3.5 mm thick tungsten absorber plates (20 X0)
- Silicon or GaAs sensors (5x5 mm2 pads, 320 (500) µm thick), installed in 1mm gap between absorbers;
- Small Molière radius, high spatial resolution of local energy deposits
- Readout via dedicated FLAME ASIC (developed in FCAL).

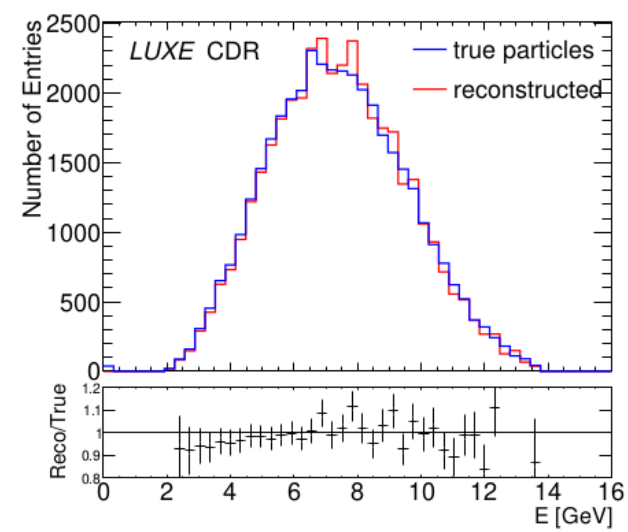
Performance in MC simulation

- Energy resolution ~19%;
- Single particle position resolution ~0.8 mm at 10GeV;
- Complementary measurement of positron energy spectra;
- Low energy distributed background rejection.



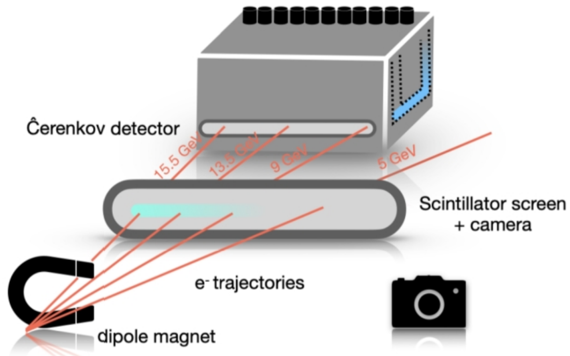
Special algorithm for high multiplicity events

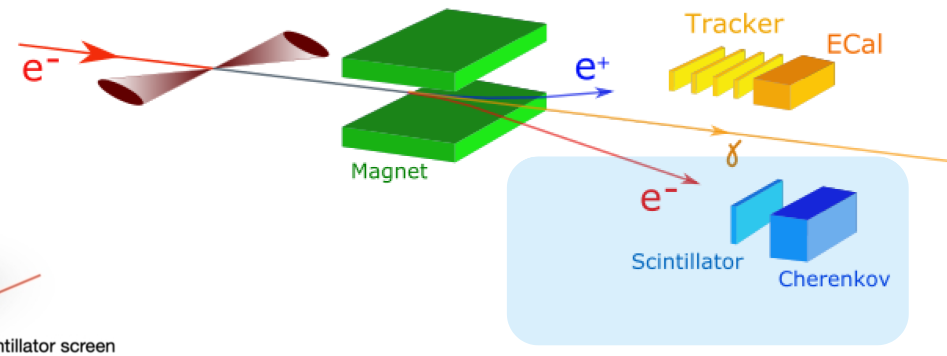
capable of reconstructing spectra and number of particles based on distribution of deposited energy



Electron Detection

- Expected event rate: up to 10^9 electrons;
- Chosen technology:
  - Scintillator screen,
  - Cherenkov gas detector.



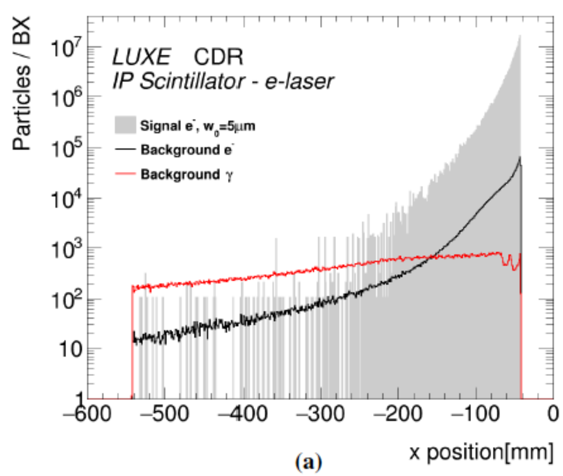


Scintillator Screen

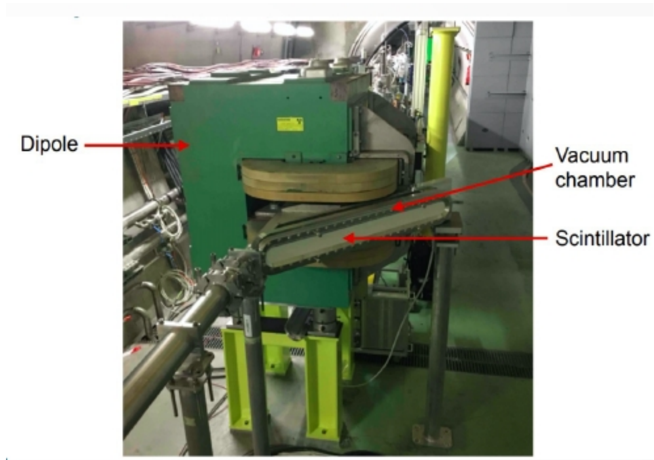
- Technology used by AWAKE experiment at CERN;
- High resolution CMOS camera takes pictures of scintillation screen as it emits the light;
- Scintillator: Tb-Doped Gadolinium Oxysulfide (GadOx) screen;
- Radiation hard (up to 10 MGy).

Performance

- Signal/background ~100;
- Position resolution <0.5 mm (~50 MeV);
- Sufficiently high dynamic range (40dB).



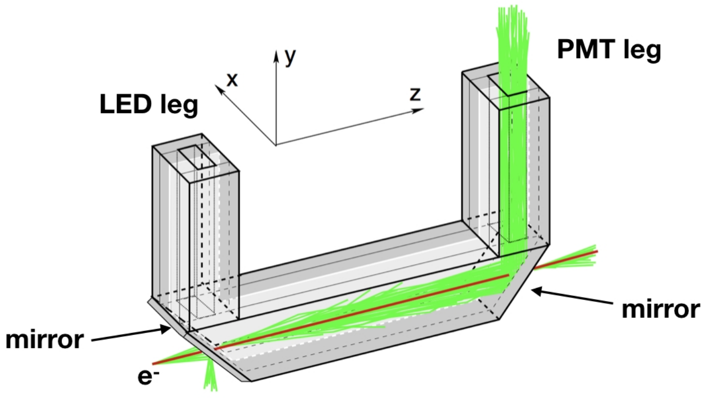
Magnet and scintillation screen attached to the widow of the vacuum chamber in AWAKE experiment



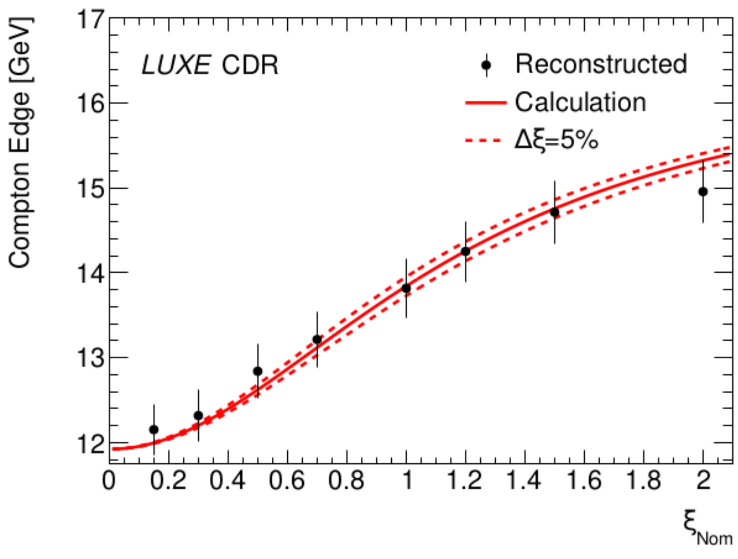
AWAKE Coll., *Nature* **561,** 363–367 (2018)
https://www.nature.com/articles/s41586-018-0485-4

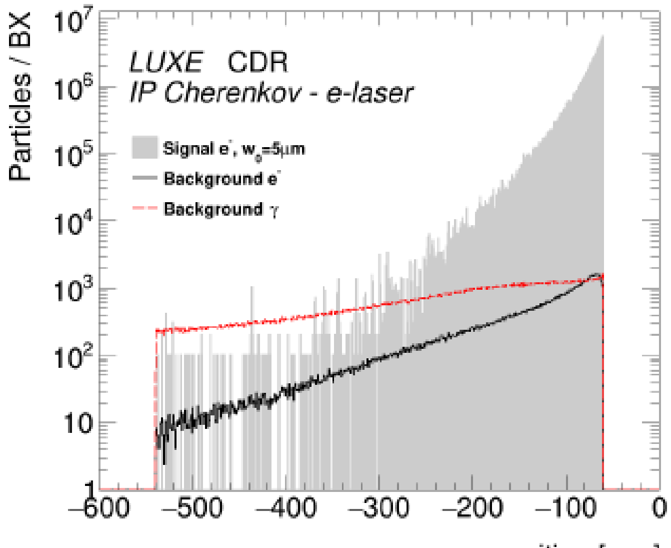
Cherenkov Detector

- Gaseous (Ar) Cherenkov detector;
- Initially developed for ILC polarimeter;
- Low refractive index gas (Ar), optical filter and optimized gas volume to reduce light yield;
- Fine segmentation to resolve kinematic edges in Compton spectra
- Not sensitive to electrons <20 MeV and photon background;
- Signal/background >1000



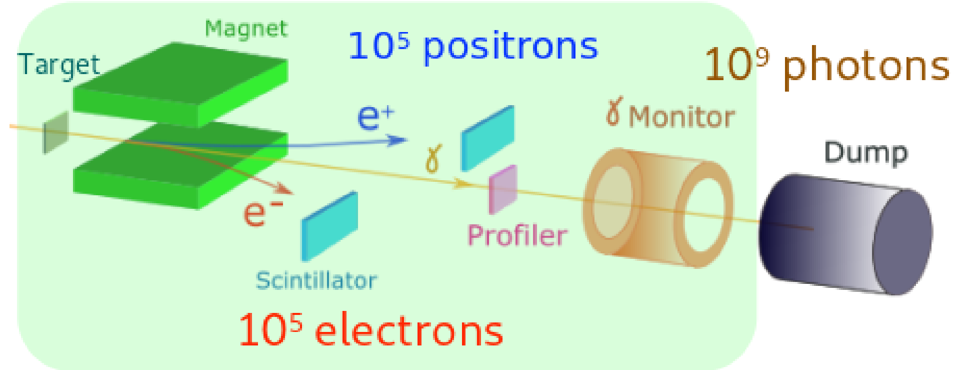
Kinematic edge reconstruction in Compton electrons spectra





(b)

Photon Detection System

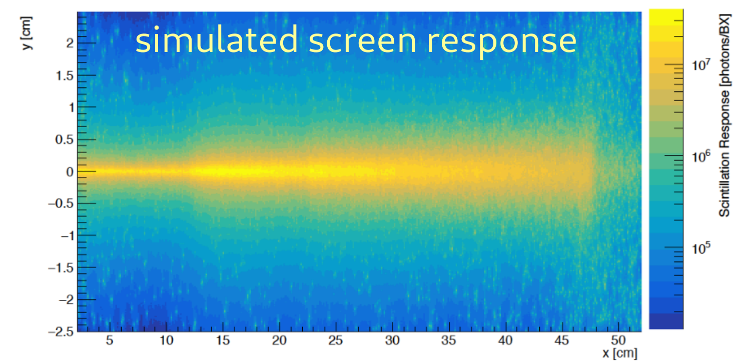


High number of photon:

- up to 10^9 photons;
- summing up to TeV energies.

Three technologies:

- Tungsten convertor target (10 μm) generates 10^4 - 10^5 electron/positron pairs;
- Spectrometer with LANEX scintillator screens coupled with photo cameras (implementation is similar to electron spectrometer):
  - Measure energy spectrum and flux.
- Gamma profiler made of sapphire strip sensors:
  - Measure transverse profile of the beam.
- Backscattering calorimeter:
  - Measure flux.

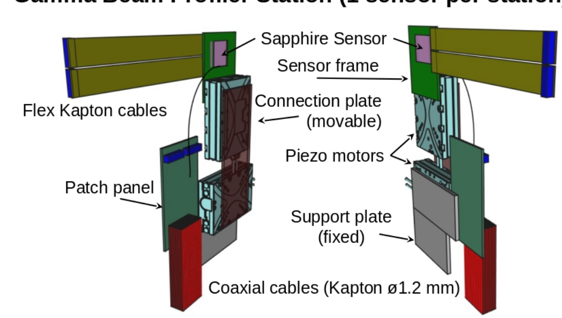


Gamma profiler

For linearly polarized laser the asymmetry in transverse profile of photon beam depends on laser intensity (ξ).

- Two sapphire strip detectors placed on a table movable with micron precision in both directions perpendicular to beam.
- 2 sensors 2 × 2 cm^2 (100 μm thickness) with 100 μm strip pitch
- very radiation hard material (up to 10 MGy)
- 5% precision in laser intensity reconstruction.

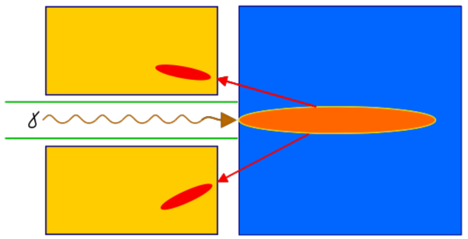
Gamma Beam Profiler Station (1 sensor per station)



Photon Flux Monitor

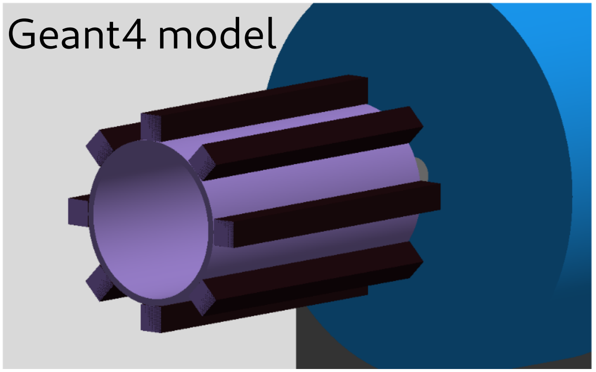
- Measure energy flow of particles back-scattered from the photon beam dump.
- Optimization of the design:
    - Reduce radiation load to provide reasonable lifetime
    - Measure sufficient fraction of the energy of the back scattering particles to be sensitive to the direct photon flux variation

For $\xi > 1$, $N\gamma > 10^8$ / BX



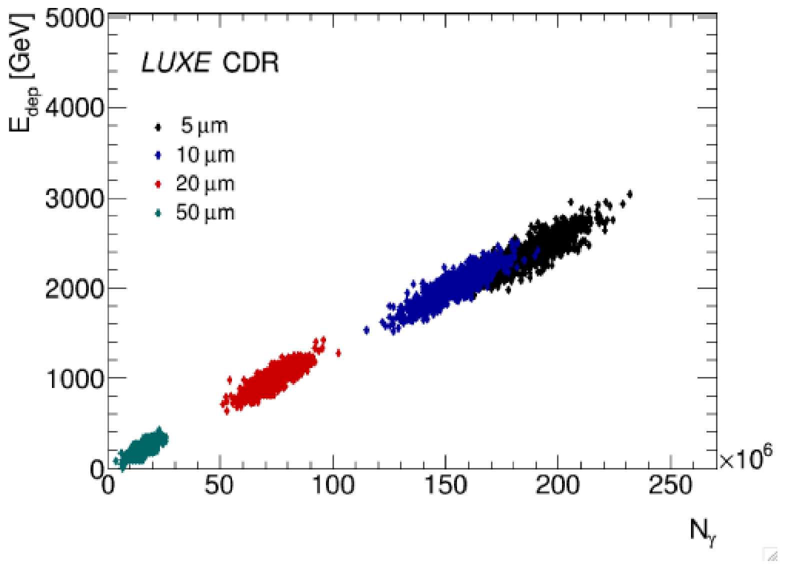
Design:

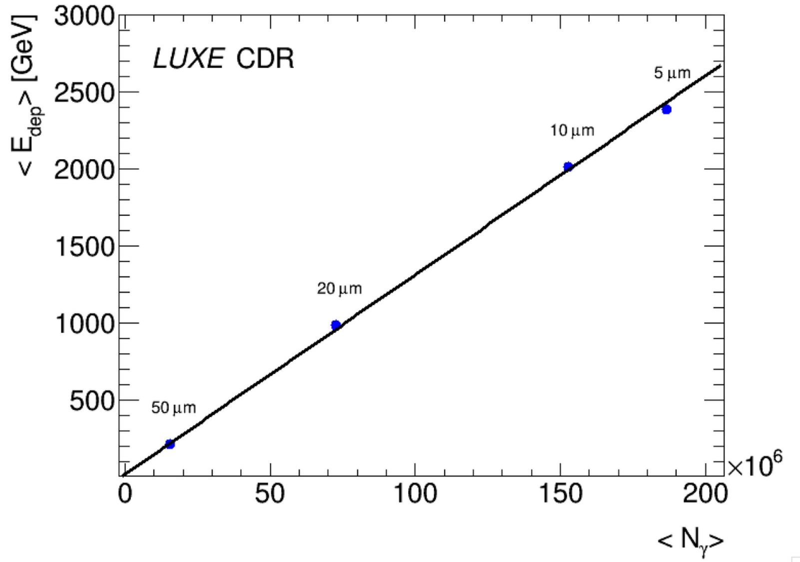
- 8 lead glass blocks, $3.8 \times 3.8 \times 45\ cm^3$
- Placed on cylinder surface with R = 120 mm.



Performance in simulation:

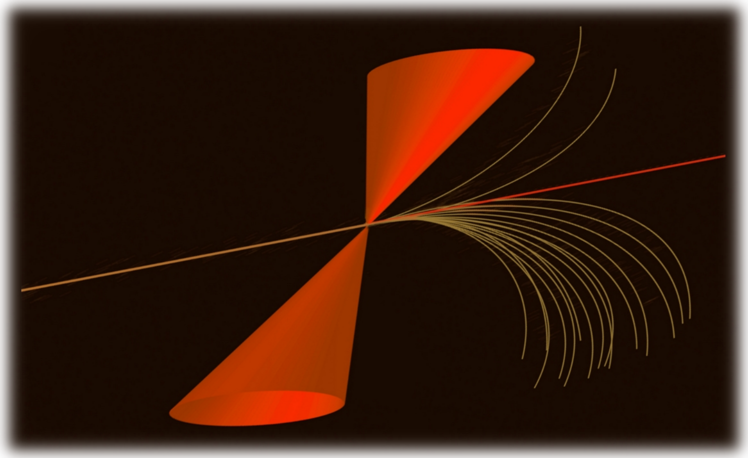
- Almost linear dependence of the deposited energy and the number of incident photons.
- Estimated uncertainty is 3-10%





Summary

- Luxe experiment presents an exciting opportunity to explore QED in new regime using European XFEL and high power laser
- Designed detector systems will allow LUXE to achieve physics goals in experimental measurements
- The design of the experiment provide its operation without interference with main EU.XFEL program
- Luxe conceptual design report received positive DESY Physics Review Committee feedback with strong recommendation to proceed with Technical Design Report
- Goal is installation in 2024 during extended shutdown planned for European XFEL



Backup

LUXE participants