PROCEEDINGS OF SCIENCE

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

Oleksandr Borysov[a,*]
on behalf of LUXE Collaboration
[a] *Weizmann Institute of Science*
234 Herzl St., Rehovot, Israel
E-mail: oleksandr.borysov@weizmann.ac.il

The LUXE experiment aims to study 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 experiment will measure the spectra of electrons, positrons and photons in expected rates ranging from 10^{-3} to 10^{9} per 1 Hz bunch crossing, depending on the laser power and focus. These measurements have to be performed in the presence of low-energy high radiation-background. To meet these challenges, for high-rate electron and photon fluxes, the experiment will use Cherenkov radiation detectors, scintillator screens, sapphire sensors, as well as lead-glass monitors for backscattering off the beam-dump. A four-layer silicon-pixel tracker and a compact electromagnetic silicon tungsten calorimeter will be used to measure the positron spectra. The layout of the experiment and the expected performance under the harsh radiation conditions are presented.

The European Physical Society Conference on High Energy Physics (EPS-HEP2023)
21-25 August 2023
Hamburg, Germany

*Speaker

PoS(EPS-HEP2023)513

1. Introduction

Quantum electrodynamics (QED) with a strong electromagnetic field has been studied since the formulation of the QED. The scale of the strong field is known as the Schwinger critical field

$$\mathcal{E}_{\rm cr} \equiv \frac{m_e^2 c^3}{e\hbar} \approx 1.3 \times 10^{16} \ \frac{\rm V}{\rm cm} \ . \tag{1}$$

where m_e and e are electron mass and charge respectively, c is a speed of light and $\hbar$ is reduced Plank's constant. This field accelerates an electron to the energy equivalent to its mass at a distance of the Compton wavelength $\lambda\!\!\!^{-} = \hbar/mc$, and leads to a possibility of spontaneous e^+e^- pair generation. A static field of this magnitude is not reachable in the lab frame, but this regime of QED can be probed in collisions of high energy electrons or photons with an intense laser beam as the fields are Lorentz-boosted. Two strong-field phenomena have been extensively studied theoretically [1–4]: non-linear Compton scattering and nonlinear Breit-Wheeler:

$$e^- + n\gamma_L \rightarrow e^-\gamma \, , \tag{2}$$

$$\gamma + n\gamma_L \rightarrow e^+e^- \, , \tag{3}$$

where n is the number of laser photons γ_L participating in the process. The interaction between high energy particle and laser fields can be characterized by an intensity parameter related to the field strength:

$$\xi = \frac{e\mathcal{E}_{\rm L}}{m_e c \omega_L} = \frac{m_e c^2 \mathcal{E}_{\rm L}}{\hbar\omega_L \mathcal{E}_{\rm cr}} \tag{4}$$

where $\mathcal{E}_{\rm L}$ is the RMS of the laser electric field and ω_L its frequency.

A pioneer experiment to study strong field QED processes was performed at SLAC by E144 collaboration [5]. It is followed by recent experiments in Astra-Gemini laser facility [6], future planned experiments in European Extreme Light Infrastructure (ELI) [7] and E320 at FACET II facility at SLAC.

The proposed LUXE (Laser und XFEL [8] Experiment) [9, 10] aims to study non-perturbative QED processes (2), (3) using the European XFEL electron beam and high power optical laser probing novel domain of field strength. The detector system of the experiment is designed also to be potentially capable to study vacuum birefringence [11, 12], radiation reaction [13] and effects of polarization of the laser and high energy photons.

The differential cross section of non-linear Compton scattering (2) as a function of the photon energy is presented in Fig. 1 for different laser intensity parameters and the XFEL electron beam with an energy of 16.5 GeV. For the lowest shown value of ξ the spectrum is mainly determined by the electron interacting with a single photon of the laser field and exhibits a characteristic kinematic edge at $E \approx 4.6$ GeV. With increasing ξ from 0.01 to 2 the rate of Compton scattering increases by more than four orders of magnitude and includes the contributions from the processes where electron interacts with two, three and more photons of the laser field. For ξ in the range (0.01, 0.5) there are distinguishable first and second kinematic edges which correspond to one- and two-photon interactions. The measurements of the Compton scattering rate and spectra of electrons and photons with their specific feature is a part of the physics program of the LUXE experiment.

PoS(EPS-HEP2023)513

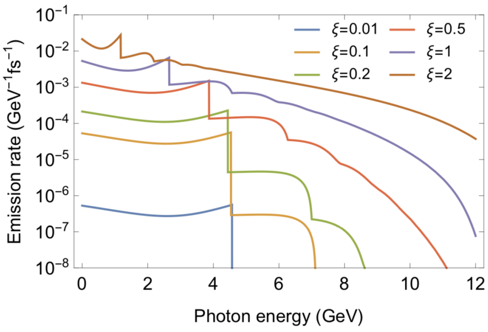

Figure 1: The rate of non-linear Compton scattering in collisions of 16.5 GeV electrons with 800 nm laser and crossing angle of 17.2°.

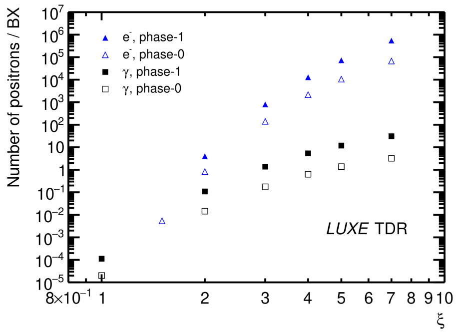

Figure 2: Number of positrons predicted by a MC simulation of non-linear Breit-Wheeler process in collisions with a laser pulse.

Several possibilities are considered for studying the non-linear Breit-Wheeler process of electron positron pair production in the interaction of high energy photon with the laser field (3). The first possibility corresponds to the case, when the photon, produced in process (2), propagating through the laser field, generates electron-positron pair in the same collision, where it was produced by electron beam [14]. In the baseline design of the experiment the high-energy photons are generated significantly upstream of the main interaction point (IP) via bremsstrahlung [1, 2]. The inverse Compton scattering (ICS) with high frequency laser is also investigated as a possible source of high energy photons.

The numbers of electrons and positrons, their spectra and kinematics were evaluated using strong field QED Monte Carlo (MC) simulations [15, 16], based on the locally monochromatic approximation (LMA) [17] and realistic electron and laser beam parameters [9]. The number of particles are shown in Fig. 2 as a function of the laser intensity parameter for different sources of high energy photons and their values span over ten orders of magnitude. This report describes the results of simulation study and optimization of the LUXE setup for achieving its physics goals in challenging experimental environment.

2. LUXE setup

As follows from Eqs (2), (3), in final states LUXE will measure electrons, positrons and photons and the setup of the experiment conceptually consists of electron and positron spectrometer, photon spectrometer and photon measuring subsystems. As the initial particles in these processes are different, LUXE will run in two modes referred to hereafter as e-laser when initial particle is electron and γ-laser when it is high energy photon.

A sketch of the LUXE experimental setup is presented in Fig. 3 for the e-laser mode. In this scenario the electron beam collides with the laser pulse at the IP located in the vacuum of the interaction chamber. Particles, produced in the collision, are confined to the narrow cone along the primary beam and propagate towards the electron and positron spectrometer which consists of a dipole magnet and a collection of detectors in electron and positron arms. The photon spectrometer, further downstream, consists of thin tungsten converter, dipole magnet and detectors for electron and positrons produced in the target. Most of the photons do not interact with the target material and are measured in the photon detector subsystem, where the gamma profiler determines the spatial distribution of the photons in the transverse plane and the gamma monitor measures their numbers.

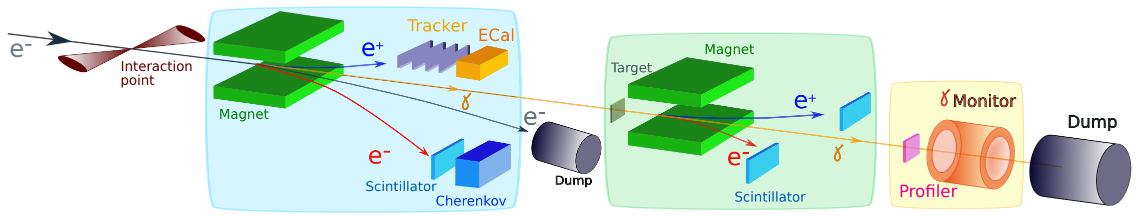

Figure 3: Diagram of the LUXE experiment layout. Shaded areas indicate electron positron spectrometer (blue), photon spectrometer (green) and photon detector (yellow) subsystems.

The optimization of the setup and detector performance study were carried out in simulation using the GEANT4 [18] framework. The design of the detectors and chosen technologies are determined by the number of particles to be measured, the required accuracy and the background level. The background is substantially enhanced by the unavoidable presence of three beam dumps located few meters away from the detectors in experimental area. Detailed simulation is used for designing the dumps and positioning shielding.

The number of electrons per bunch crossing (BX) expected in detectors varies substantially depending on the LUXE run mode and detector location in the experiment. There are several subsystems where the particle numbers exceed 10^5. All of them are equipped with scintillator screens coupled with high resolution CMOS cameras which take a picture of the screen as it emits the light. This technology has been successfully used in the past and it provides position resolution better than 0.5 mm and up to 10 MGy radiation hardness for considered Tb-doped Gadolinium Oxysulfide screen. The sensitivity of the screen to the photons is essentially determined by their conversion, and since the thickness of the screen is about 0.5 mm, it is negligible which provides a good rejection of the photon background. The electron arm of the first spectrometer is also equipped with highly segmented gas Cherenkov detector. It provides complementary measurements of electron spectra with efficient rejection of the background represented by low energy charged particles.

The considered number of positrons per BX ranges from 10^{-2} up to 10^4. The detection of small numbers of positrons requires excellent efficiency of the detector and robust background rejection. This background is substantial, considering the fact that the initial bunch comprises $1.5{\times}10^9$ electrons and the beam is dumped in the experimental area. For this purpose the positron detector system consists of four layers of ALPIDE pixel sensors followed by an ultracompact electromagnetic calorimeter (fig. 4). The pixel sensors are assembled in staves, two of which in each layer completely cover the expected spectra of positrons shown in Fig. 5. The performance study of the tracker in GEANT4 simulation demonstrated efficiency close to 100% and energy resolution better then 1%. Ultracompact sampling electromagnetic calorimeter provides positron energy measurement and rejection of low energy charged particles background to which the tracker is sensitive.

The gamma profiler consists of two 100 μm thick sapphire strip sensors and provides measurement of the photon distribution in the transverse plane with a resolution of about 5 μm. The sensors also have sufficient radiation hardness to operate during experiment run period. The gamma monitor is a calorimeter which measures the energy carried by particles backward from the photon beam dump. It was established in simulation studies that the energy deposited in calorimeter by back-scattered particles is nearly proportional to the number of photons in the beam which hit the dump. This allows measuring the number of photons with 5% - 10% accuracy.

For the γ-laser scenario, the number of electrons produced at the IP in the non-linear Breit-Wheeler process is identical to the number of positrons hence the same pixel tracking detector and a calorimeter will be used for their registration. These detectors need to be installed on the movable platform capable of lifting them when the experiment switches from e-laser to γ-laser mode.

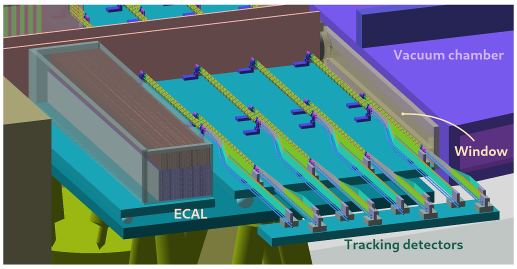

Figure 4: Positron detector GEANT4 model includes vacuum chamber, window, four layers of tracking detectors followed by calorimeter.

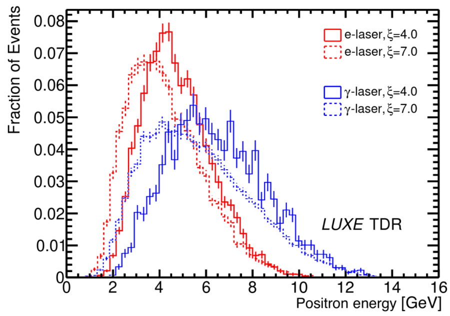

Figure 5: The positron energy spectrum for the e-laser and the γ-laser modes.

3. Summary

LUXE at DESY proposes to extend the scientific scope of European XFEL to probe fundamental physics in the new regime of strong fields in a way that is transparent to the photon science program. Experimental study of laser assisted pair production and high intensity Compton scattering is feasible with European XFEL beam, combined with a multi-terawatt, high-intensity laser. The simulations with designed LUXE experimental setup and detector test beam campaigns show that the detector subsystems can be built using existing technologies and they can provide measurements with required accuracy while withstanding harsh experimental environment.

4. Acknowledgements

This work was in part funded by the Deutsche Forschungsgemeinschaft under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306 and the German-Israel Foundation (GIF) under grant number 1492. It has benefited from computing services provided by the German National Analysis Facility (NAF).

References

[1] A. Hartin, A. Ringwald, and N. Tapia, *Measuring the boiling point of the vacuum of quantum electrodynamics*, Phys. Rev. D **99** (2019) 036008. [arXiv:1807.10670].

[2] T.G. Blackburn and M. Marklund, *Nonlinear Breit-Wheeler pair creation with bremsstrahlung γ rays*, Plasma Phys. Control. Fusion **60** (2018) 054009.

[3] Howard R. Reiss, *Production of Electron Pairs from a Zero-Mass State*, Phys. Rev. Lett. 26, (1971) 1072.

[4] A. Fedotov, A. Ilderton, F. Karbstein, B. King, D. Seipt, H. Taya, G. Torgrimsson, *Advances in QED with intense background fields*. [arXiv:2203.00019]; RIKEN-iTHEMS-Report-22.

[5] C. Bamber *et al*, *Studies of nonlinear QED in collisions of 46.6 GeV electrons with intense laser pulses*, Phys. Rev. D **60**, (1999) 092004.

[6] J.M. Cole *et al*, *Experimental evidence of radiation reaction in the collision of a high-intensity laser pulse with a laser-wakefield accelerated electron beam*. Phys.Rev. **X8** (2018) no. 1, 011020. [arXiv:1707.06821].

[7] N. V. Zamfir, *Extreme Light Infrastructure - Nuclear Physics (ELI-NP) European Research Centre*, EPJ Web Conf. **66**, (2014) 11043.

[8] M. Altarelli *et al*, *European X-ray Free Electron Laser. Technical Design Report*, ISBN 978-3-935702-17-1 (2006), DOI:10.3204/DESY_06-097.

[9] H. Abramowicz *et al*, *Conceptual Design Report for the LUXE Experiment*. Eur. Phys. J. Spec. Top. (2021) 230:2445–2560. [arXiv:2102.02032].

[10] H. Abramowicz *et al*, *Technical Design Report for the LUXE Experiment*. [arXiv:2308.00515].

[11] O. Borysov, B. Heinemann, A. Ilderton, B. King, A. Potylitsyn, *Using the nonlinear Breit-Wheeler process to test nonlinear vacuum birefringence*. Phys. Rev. D**106**, 116015 (2022). [arXiv:2209.12908].

[12] B. King, T. Heinzl, T. G. Blackburn, *Strong field vacuum birefringence in plane wave pulses*. Eur. Phys. J. C (2023) 83:901.

[13] B. King, Classical Radiation Reaction in Red-Shifted Harmonics. [arXiv:2305.14429].

[14] S. Tang and B. King, *Locally monochromatic two-step nonlinear trident process in a plane wave*. Phys.Rev. D**107**, 096004.

[15] T. G. Blackburn, A. J. MacLeod, B. King, *From local to nonlocal: higher fidelity simulations of photon emission in intense laser pulses*, New J. Phys. 23, 085008 (2021). [arXiv:2108.10883].

[16] T. G. Blackburn, B. King and S. Tang, *Simulations of laser-driven strong-field QED with Ptarmigan: Resolving wavelength-scale interference and γ-ray polarization*. Phys.Plasmas 30, 093903 (2023).

[17] T. Heinzl, B. King, and A. J. MacLeod, *Locally monochromatic approximation to QED in intense laser fields*, Phys. Rev. A 102, 063110

[18] J. Allison *et al*, *Recent developments in GEANT4*, NIM A **835**, 186 (2016).