PROCEEDINGS OF SCIENCE

LUXE: a high precision experiment to study non-perturbative QED in electron-laser and photon-laser collisions

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The LUXE experiment (Laser Und XFEL Experiment) is a new experiment in planning at DESY Hamburg using the electron beam of the European XFEL (Eu.XFEL). LUXE is intended to study collisions between a high-intensity optical laser and up to 16.5 GeV electrons from the Eu.XFEL electron beam, or, alternatively, high-energy secondary photons. The physics objective of LUXE are processes of Quantum Electrodynamics (QED) at the strong-field frontier, where QED is non-perturbative. LUXE is also able to probe different forms of new physics beyond the standard model of fundamental particles and forces, in particular through the concept of New Physics Optical Dump searches. The design of the experimental setup and the different detectors are presented.

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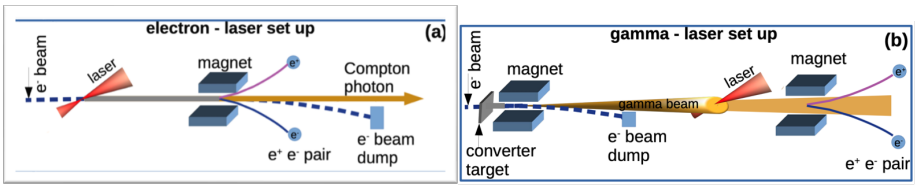
1. Introduction

Quantum Electrodynamics (QED) is a well-tested and well-understood theory. The perturbative calculations are precise; however, in the presence of strong fields, perturbative QED breaks down and becomes non-perturbative. Above a critical value of the field (the "Schwinger limit"[1]), the vacuum becomes polarized and there is a production of electron-positron pairs [2]. The LUXE [3] experiment at DESY and the European XFEL (Eu.XFEL) in Hamburg is intended to study strong field QED processes using collisions between a high-intensity laser (40 TW in the initial state of the experiment, Phase-0, and a 350 TW in the second stage, Phase-1) and a 16.5 GeV electron beam. Depending on the beam parameters, the particle flux will lay between 10^{-4} to 10^{9} particle per laser bunch; we will present the different sub-detectors and their design to cope with such rates.
The two setups for the beam lines are presented in Figures 1a and 1b. In both setups, the electron beam and the laser have a rate of 10 Hz and 1Hz respectively. In the case of the photon-laser interaction a target is placed in the electron beam to create conversion of photons. Then the electron beam is deviated by a magnet, the photon beam is produced and interacts with the laser beam.



(a) **(b)**

Figure 1: a) Electron-laser interaction setup, b) Photon-laser interaction setup.

Due to the high photon flux, the design of the experiment makes it additionally sensitive to the production of new spin-0 particles via photon-dump interaction: photons traverse the experimental setup (in vacuum) and reach a physical dump at its end, where their interaction with the material nuclei leads to the production of axion-like particles (ALP). The decay volume following the beam dump ends with a detector designed to allow the reconstruction of the two photons resulting from the decay of the ALPs.

2. Physics processes

It is important to introduce two parameters which are relevant in the laser-electron interactions: the first one is the classical non-linearity parameter of the laser field,

$$\xi = \frac{m_e c^2 E}{\hbar \omega_L E_{cr}}$$

where ω_L is the laser wavelength, E is the electromagnetic field strength, and E_{cr} is the Schwinger critical field, characterizes the coupling between the high-intensity laser and the probe electron. It can be understood as proportional to the laser intensity. When $\xi \ll 1$, QED is fully perturbative and

when $\xi \gg 1$, QED starts to be non-perturbative. The second parameter is the quantum parameter:

$$\chi_e = \frac{E^*}{E_{cr}}$$

which, in the case of electron-laser interaction, quantifies the ratio of the field strength in the rest frame of the electron (E^*) and the critical field. In Figure 2, it is possible to see the potential coverage of the LUXE experiment (for different laser powers and focal spots) with respect to past and nowadays experiments.

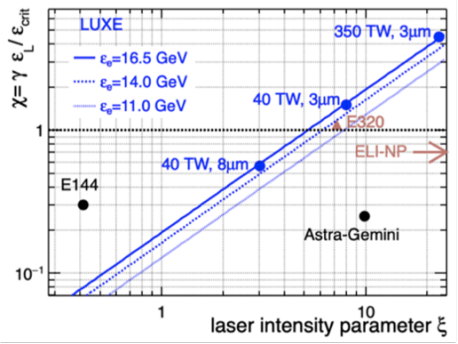
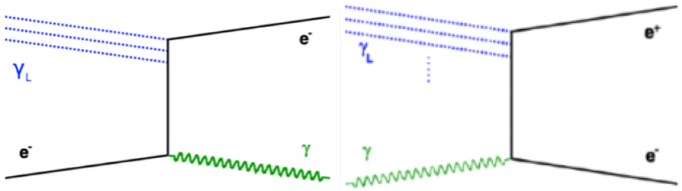


Figure 2: Potential coverage of LUXE compared to a past experiment (E144) and nowadays experiments (SLAC-E320 (US), Astra Gemini (UK), ELI-NP (RO)).

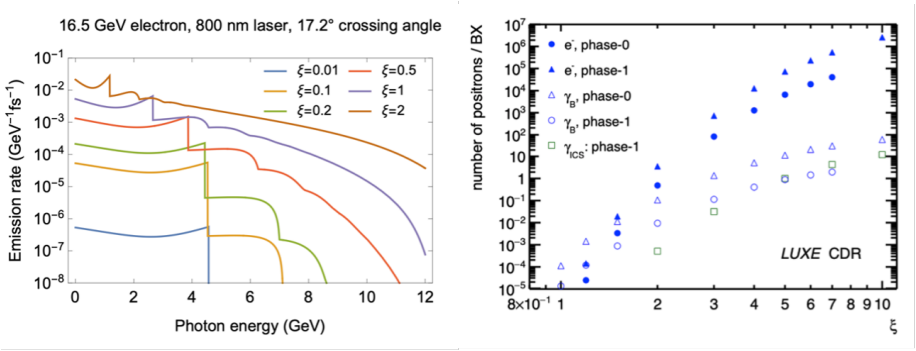
For electron-laser interactions, the main processes are the non-linear Compton scattering (Figure 3a) in the case of an electron-laser mode and the non-linear Breit-Wheeler pair production process (Figure 3b), in the case of photon-laser mode.



(a) **(b)**

Figure 3: a) Non-linear Compton scattering and b) non-linear Breit-Wheeler pair production.

The numbers of photons and positrons produced have been simulated and the results are shown in Figure 4a and 4b respectively. The edges in the photon spectra correspond to the interaction of the electron with several photons of the laser field: the first edge to the interaction with one photon, the second to the interaction with two photons, and so on. The positron rate varies between 10^{-1} and 10^6 per bunch crossing, in electron-laser mode.



(a) **(b)**

Figure 4: a) Photon rate (by energy) resulting from non-linear Compton scattering for a 16.5 GeV electron colliding with laser pulses at various values of the intensity parameter ξ ,b) Number of positrons per bunch crossing predicted by an MC simulation of a non-linear Breit-Wheeler process. Different markers correspond to different sources of the initial photons (Bremstrahlung , Inverse Compton Scattering).

The detectors should be capable of detecting electrons, positrons, and photons with energies on the order of a few GeV, while providing both flux measurements and energy spectra (in two different beam configurations). The chosen detector technologies must be able to handle signal and background fluxes ranging from 10^{-4} up to 10^{9} particle per laser bunch crossing.

3. The LUXE detection system

The LUXE experiment is designed to analyse electron-laser and photon-laser interactions as well as photons interacting in the photon beam dump. It is therefore necessary to measure the multiplicities and the energy spectra of electrons, photons and positrons Sketches of the layout of the experiment for e-laser and γ-laser modes are shown in Figure 5.

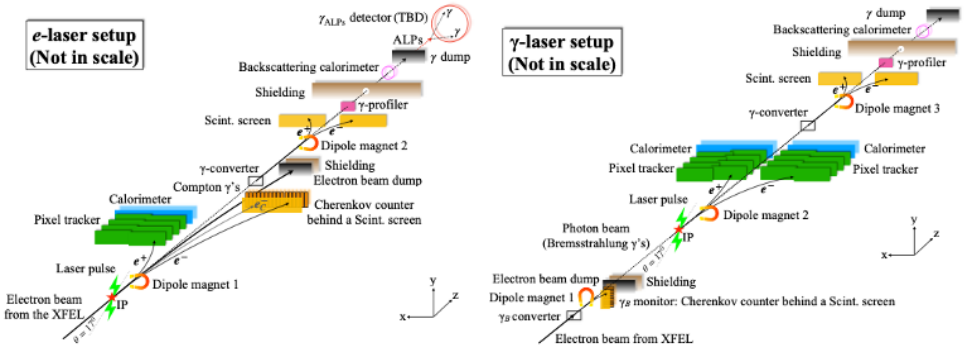


Figure 5: Schematic layouts for the e-laser (left) and γ-laser (right) setups. Shown are the magnets, detectors and main shielding and absorbing elements.

In γ-laser mode, a target chamber is installed to convert the electron beam to a photon beam either by bremsstrahlung on a tungsten target or via inverse Compton scattering on a low-intensity

laser beam. Then a dipole magnet will separate electrons and positrons from the photon beam. In the e-laser mode the magnet is turned off.
After the interaction point (electron or photon beam colliding with the high-power laser), a magnet will separate the positrons (left side) and the electrons (right side) produced.

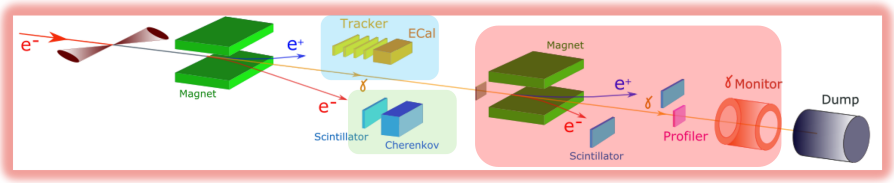


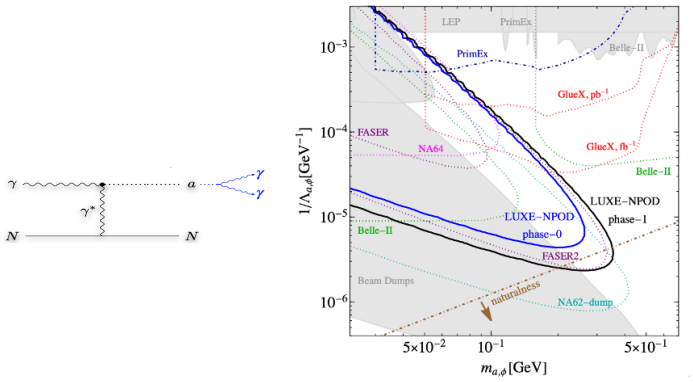
Figure 6: Schematic layout of the e-laser experimental setup: the positron setup is shown in blue, the electron setups in green, and the photon detection setup in red.

The positron detection shown in Figure 6 (blue) consists of a pixel tracking built from ALPIDE silicon pixel chips [4] organized in staves (27×1.5 cm^2). These staves are already being used by the ALICE collaboration in their barrel inner tracking system. In LUXE, there will be four consecutive staves organized in a planar geometry, facing the beam. Located after the tracker, a high-granularity compact electromagnetic calorimeter will be installed. It is a sampling calorimeter composed of 20 layers of 3.5 mm thick tungsten absorber plates and silicon sensors (5×5 mm^2 pads). The compactness is limited by the inherent Moliere radius of the passive absorber, with tungsten providing the smallest Moliere radius. The readout will be based on a novel multi-channel, ultra-low power (5 mW/channel) readout ASIC FLAME, consisting of an analog front-end with variable gain and of a fast sampling (20 MSps) 10-bit ADC converter in each readout channel. A dedicated version, FLAXE, will be adapted to the LUXE experimental conditions (low trigger rate). In the e-laser case, the flux of Compton-scattered electrons after the interaction point (IP) varies between 10^5 and 10^9 particle per laser bunch crossing, depending on the laser intensity parameter. A high-flux detection system consisting of a scintillator screen imaged by an optical camera, and a spatially segmented gaseous Cherenkov detector which measure the flux of particles as a function of their deflection in the dipole magnetic field is presented in Figure 6 (green). The scintillator screen, in combination with a high-resolution CMOS camera, provides spatial resolution better than 500μm. The Cherenkov detector, consisting of an array of segmented straws read out by silicon photo-multipliers, measures the particle flux as a function of their deflection in the dipole magnetic field, thereby enabling efficient rejection of low-energy background particles.
Then, the photon area, shown in Figure 6 (red), hosts a photon detection system which is designed to measure the photon flux, angular and energy spectrum of the photons produced at the IP in e-laser mode, or that fly through in the γ-laser mode. The energy spectrum is determined using a gamma spectrometer. The gamma ray spectrometer is based on a conversion target and electron and positron spectrometers using a detection system consisting of scintillating screens and cameras. The spectrometer is followed by a gamma beam profiler, designed to accurately measure the transverse profile of high-intensity gamma-ray beams with a spatial resolution of 5μm using sapphire strip detectors. Finally, there is a gamma flux monitor (GFM) precisely monitoring the rate and possibly ascertain the angular distributions of photons, in a photon flux exceeding 10^8 mm^{-2} per bunch

crossing. The GFM measures the energy flow of back-scattered particles from the photon beam dump using a homogeneous calorimeter built of lead-glass blocks with optical readout.

4. New physics search

In addition to probing strong-field QED physics processes, the large flux of high-energy photons arriving at the final optical beam dump, can be used for the production of axion-like particles (ALPs) via the Primakoff mechanism (Figure 7a) resulting from the γ-matter interaction.



(a) **(b)**

Figure 7: a) Primakoff process to produce ALPs, b) result of a sensitivity study for detection of ALPs in the LUXE optical beam dump is compared to other experiments in terms of the ALP mass and coupling strength.

LUXE can take advantage of this fact and perform a competitive search for ALPs [5] using a calorimeter placed after final dump. By placing a calorimeter at a fixed distance behind the photon dump (New Physics Optical Dump) and ensuring a low background in this detection area, decays of the ALPs to two photons can be probed. The outcome of a sensitivity study for this ALP search is summarized in Fig.7b, using a $1 \times 1\text{m}^2$ calorimeter.

5. Conclusion

LUXE will probe QED in a new regime of strong fields, by studying collisions between the Eu.XFEL electron beam, or a high-energy secondary gamma photon beam, with a high intensity optical laser. Running LUXE as a collision experiment in continuous data-taking mode will enable precision measurements of strong-field QED processes, such as non-linear Compton scattering and Breit-Wheeler pair production. LUXE will likely be the first experiment to take precision measurements in a regime of QED never before explored in clean laboratory conditions, with long-term availability of continuous data-taking time and to study high-intensity laser collisions with real high-energy gamma photons.
In addition, the experimental setup offers the possibility to search for physics beyond the Standard Model by installing a dedicated calorimeter downstream of the final dump, enabling the detection of weakly interacting or long-lived particles that could escape the primary interaction region.

6. Acknowledgment

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