PROCEEDINGS OF SCIENCE

LUXE: a new experiment to study non-perturbative QED and search for new particles in electron-laser and photon-laser collisions

Evan Ranken[a]
on behalf of the LUXE collaboration

[a] *Deutsches Elektronen Synchrotron DESY, Notkestraße 85, D-22607 Hamburg, Germany*

E-mail: evan.ranken@desy.de

LUXE is a proposed near-future experiment along the European XFEL beamline aiming to make several new measurements in the non-perturbative regime of strong-field quantum electrodynamics (SFQED). The experiment will collide electrons and photons with a high-intensity laser in order to measure multiple non-linear processes unique to the extreme realm of SFQED, allowing the first chance to validate theoretical models in this unexplored regime. The photon-laser collisions in particular will be unique to LUXE, offering the most direct demonstration of electron-positron pair production from the QED vacuum at extreme field strengths. Additionally, the large quantities of photons reaching the final beam dump of the experiment will be utilized in a search for long-lived, axion-like particles which are candidates for dark matter. A variety of complimentary detector systems are used to ensure precise results and accurate calibration. The theoretical background and experimental program are briefly outlined, in order to give a broad view of the experimental goals.

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

PoS(EPS-HEP2023)289

1. Introduction

LUXE (**L**aser **u**nd **X**FEL **E**xperiment) [1, 2] is a near future experiment that will probe previously unmeasured regimes of quantum electrodynamics (QED) with electron-laser and photon-laser collisions. The experiment will utilize existing infrastructure from the European X-ray Free-Electron Laser (EuXFEL) [3] in combination with a separate high-intensity laser system. The EuXFEL begins with an injector located on the campus of the Deutsches Elektronen-Synchrotron (DESY), where a 1.9 km linear accelerator produces a beam of electrons at 16.5 GeV, with some variation of the enrergy possible. After this, the electron beam is passed through undulators, which produce coherent x-ray emission that is delivered to experimental halls in nearby Schenefeld. LUXE will With By colliding relativistic particles with an ultra-high-intensity laser pulse, LUXE will validate theoretical models which aim to describe the non-perturbative effects induced by the high effective field coupling values.

LUXE will be situated immediately after the EuXFEL linear accelerator, utilizing the electron beam as a primary source. These electrons will collide with a high-intensity laser pulse generated by a state of the art titanium sapphire laser, generating SFQED processes at intensities which have never been tested. In addition to direct use of the EuXFEL electron beam, LUXE is designed for a unique setup which converts electrons to photons prior to the main laser interaction point, either via bremsstrahlung on a tungsten target or via inverse Compton scattering on a low-intensity laser beam. At the planned intensities, this mode will allow LUXE to produce eletctron-positron pairs from the vacuum using exclusively real photons, providing the most direct confirmation to date of spontaneous matter creation from the QED vacuum state at high field intensities.

2. Strong field QED: theory and history

QED is a field theory understood primarily by means of perturbative expansion in the electromagnetic coupling constant α. When this coupling is small, the theory is famously accurate, able to calculate quantities like the electron anomalous magnetic moment to one part in a trillion. However, there are some regimes where the usual perturbative approach breaks down.

A hallmark feature of strong field QED (SFQED) is the Schwinger limit,

$$\mathscr{E}_{\text{crit}} = \frac{m_e^2 c^3}{e\hbar} \approx 1.3 \cdot 10^8 \text{Vm}\,, \tag{1}$$

at which the electromagnetic field becomes so strong that vacuum linearity breaks down. At these energy densities, the vacuum is able to spontaneously produce ee^- pairs via the Breit-Wheeler process. Such field strengths can occur in extreme astrophysical conditions like those found in magnetars, making SFQED essential for understanding their emissions. While the Schwinger limit is currently not plausible to achieve in the lab frame, it can be reached in the case of relativistic particles, which experience enhancement of the field strength in their rest frame proportional to the Lorentz factor γ: $\mathscr{E}_{\text{rest}} = \gamma \mathscr{E}_{\text{lab}}$.

In the case of an electron passing through a high-intensity laser pulse, one can understand the onset of nonlinearity as a function of the number of laser photons which are relevant in electron-lases. At low intensity, lower harmonics corresponding to small numbers of interactions dominate.

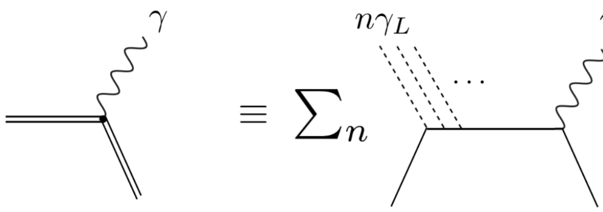

Figure 1: Definition of a "dressed" electron undergoing Nonlinear Compton scattering (NCS) in the presence of a high-intensity laser field.

But at higher field intensities, more and more interactions become relevant on the scale of the electron's Compton wavelength, and eventually the theory must sum over all possible harmonics. This summation is understood via the dressed or "Furry" picture as shown for the case of nonlinear Compton scattering (NCS) in Fig. 1.

In the case of a high-energy photon traversing a high-intensity laser field, it is possible to create a multi-photon analogue of vacuum pair production as shown in Fig. 2 (center), in which the ee^- pair are dressed by the field. This is known as nonlinear Breit-Wheeler production. The combination of these two diagrams shown in Fig. 2 (right) is often referred to as the trident process, and can occur with real or virtual photons.

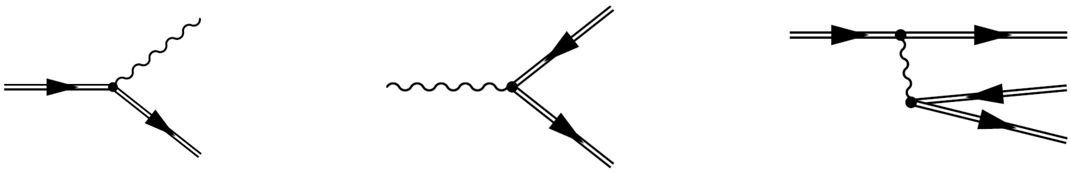

Figure 2: Three physics targets at the LUXE experiment: nonlinear Compton scattering (NCS, left), nonlinear Breit-Wheeler production (center), and the trident process (right).

One useful tool to classify the SFQED parameter space is the dimensionless intensity parameter

$$\xi = \frac{m_e}{\omega_L}\frac{\mathcal{E}_L}{\mathcal{E}_{\text{crit}}}, \tag{2}$$

where m_e is the electron mass, ω_L is the angular frequency of the laser, and $\mathcal{E}_L$ the field strength of the laser. Note that ξ depends on the laser parameters only. Physically, ξ quantifies a ratio between the work done by the field over an electron's Compton wavelength and the energy of an individual laser field quantum.

For the case of the LUXE experiment, the effect of the parameter ξ on the distribution of photons resulting from nonlinear Compton scattering is shown in Fig. 3 (left). Some hallmark features can be seen: the shifting and distortion of the sharp Compton edge, as well as the high energy tail of the distribution corresponding to higher order "harmonics" as more and more laser photons play a role in the scattering process. To measure this spectrum, one can rely on subsequent trident production, or use direct reconstruction of the scattered electrons, whose resulting energy spectra are shown in Fig. 3 (right).

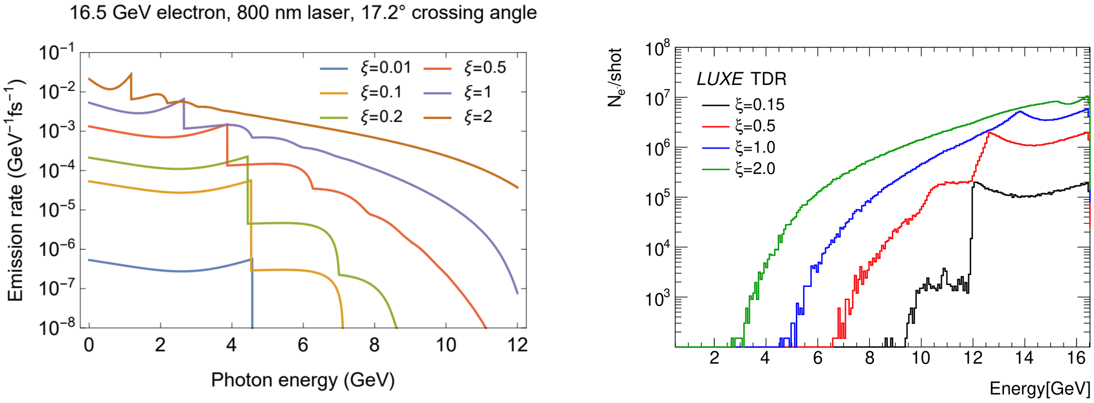

Figure 3: Photon rate (by energy) resulting from nonlinear Compton scattering for a 16.5 GeV electron colliding with laser pulses at various values of the intensity parameter ξ (left). Resulting simulated electron energy spectrum after photon emission via NCS (right).

To fully describe the interactions, we need to also consider the quantum parameter

$$\chi_i = \frac{E_i}{m_e}\frac{\mathcal{E}_L}{\mathcal{E}_{\text{crit}}} 1 \cos\theta, \qquad i = e^-, \gamma, \tag{3}$$

where i indexes over the electron e and photon γ, and θ is the crossing angle. This parameter depends on both the laser intensity and incident particle, encapsulating the ratio of the laser field intensity experienced by the incident particle to the Schwinger limit. Together, these define a useful parameter space for describing nonlinear Compton scattering in SFQED. By varying the laser intensity parameter via focusing and stretching, LUXE will be able to take measurements at a wide range of points along along a diagonal in the $\chi - \xi$ parameter space, as shown in Fig. 4.

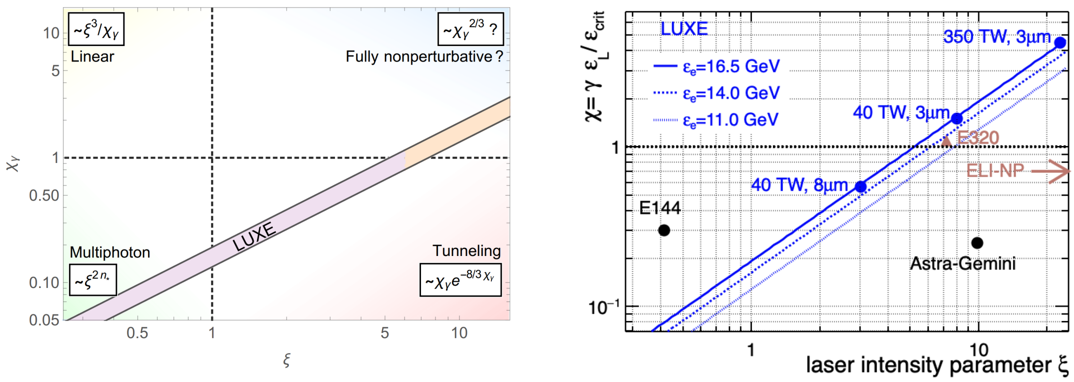

Figure 4: The expected range of the LUXE experiment in the $\chi - \xi$ parameter space of strong-field QED. In the left plot, the phase space is broadly mapped out via the dependence of photon yield on the two parameters. The right plot shows more detail on experimentally accessible points, including those reached at experimental facilities (E144 [4, 5], Astra-Gemini [6, 7]) and those reachable by some recent experimental setups (E320 [8], ELI-NP [9]).

Perhaps the most obvious predecessor to LUXE was the E144 collaboration at SLAC [4, 5], which operated during the 1990s. This experimental setup was able to measure NCS via the trident process in the perturbative, multiphoton regime (photon yield $\sim \xi^{2n}$). The nonlinear trident process was also recently observed by the NA63 experiment at CERN [10, 11] by generating strong electromagnetic fields in an oriented germanium crystal.

LUXE will be able to perform measurements of NCS via trident production occurring in vacuum conditions with multiple precise and complimentary detection systems, performing crucial validation of SFQED theory. It is also poised to be the first experiment to observe non-linear Breit-Wheeler production from a photon-laser interaction in the non-perturbative regime. To help facilitate precision validation of current theory, a bespoke SFQED simulation framework has also been developed to simulate electron-laser and photon-laser outcomes at LUXE [12].

3. Beam and Laser

The LUXE experiment will utilize 16.5 GeV electrons from the EuXFEL beam. These electrons will be delivered in bunches of 0.25 nC (1.5×10^9 electrons) at a rate of 10 Hz. Only 1 of 2700 circulating EuXFEL bunches will be used by LUXE for each shot, with a small few being potentially lost due to the beam extraction process. This will ensure negligible effects on the existing photon science program at the EuXFEL. Meanwhile, the laser system will deliver high-intensity pulses at a rate of 1 Hz, with the other 9/10 electron bunches used to record "background-only" shots useful for calibration.

The LUXE laser system will use chirped-pulse amplification [13] to obtain significantly higher values of the intensity parameter than what was possible in previous experimental generations. The design allows for the possibility to implement the laser system in two stages due to availability–an initial *phase-0* laser system followed by a more powerful *phase-1* system. The envisioned phase-0 system consists of a 40 TW laser capable of reaching a maximum intensity parameter of $\xi \approx 7.9$, while the phase-1 laser system would consist of a 350 TW laser reaching up to $\xi \approx 23.6$. Already in phase-0, values of $\chi > 1$ can be achieved, with phase-1 able to push into the uncharted fully non-perturbative regime in which $\chi \gg 1$, $\xi \gg 1$.

4. Detector design

A unique aspect of LUXE is its design to run in two separate configurations, choosing to either collide EuXFEL electrons with the laser pulse directly, or to use a Tungsten γ-converter to produce photons which would in turn collide with the laser pulse. The basic conceptual sketch and particle rates for each configuration are shown in Fig. 5. In particular, the latter "γ-laser" mode is unique to LUXE, allowing the possibility for the first measurement of nonlinear Breit-Wheeler pair production in the non-perturbative regime of SFQED.

The different particle rates seen in Fig. 5 necessitate different detection systems. For the e-laser mode in which LUXE will take first data, a scintillator screen and Cherenkov counting detector are used in tandem to measure the high rates of electrons, while a 4-layer tracking system complimented by a Calorimeter is used for lower-rate positron detection. Both detection systems function as spectrometers. These detection systems are shown as part of a more detailed schematic of the full e-laser setup in Fig. 6

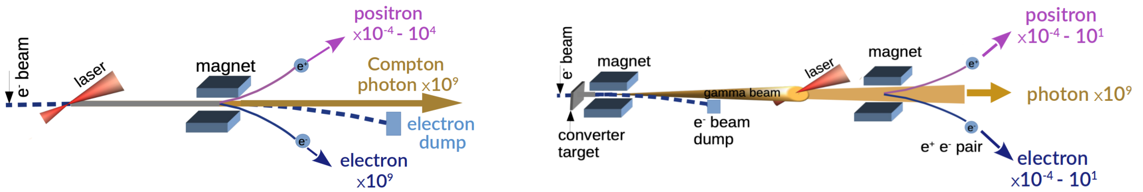

Figure 5: Configurations and typical particle rates per bunch are shown for the primary detection area immediately following the LUXE interaction point, both for the case of the e-laser configuration (left) and the γ-laser configuration (right).

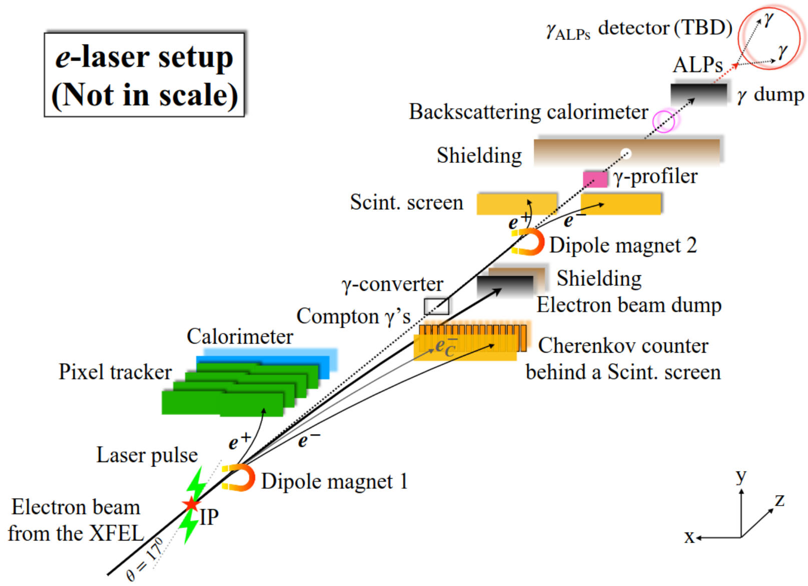

Figure 6: A detailed schematic of the experimental configuration for the initial e-laser operation mode.

For the γ-laser setup, the introduction of the converter target shown in Fig. 5 will alter particle rates and necessitate an alternative primary detection system setup. Noting that the γ-laser setup has similar e and e^- particle rates, a more symmetric configuration will be used with an electron tracker+calorimeter setup put in place to mirror the positron system. This will be performed during short EuXFEL downtime windows as part of the general setup alteration when transitioning between the two modes.

Following the electron beam dump, a large number of photons will continue on to a series of secondary detection systems. A conversion target will produce ee^- pairs which will reach a γ-spectrometer consisting of two scintillator screens. Following this, remaining photons will pass through a beam profiler made of radiation-hard sapphire, which will aid in beam monitoring and in the estimation of ξ. Finally, photons will arrive at the final γ dump, and byproducts of the resulting collision will be measured by a back-scattering calorimeter for information about the beam energy.

Due to the large flux of high-energy photons arriving at the final optical beam dump, there is the potential for the production of axion-like particles (ALPs) via the Primakoff mechanism resulting from the γ-matter interaction. LUXE can take advantage of this fact and perform a competitive search for ALPs [14] using a detector placed after final dump. This detector could also be sensitive to ALPs produced via the primary laser interaction, which may add sensitivity to other modes of ALP production. The outcome of a sensitivity study for this ALP search is summarized in Fig. 7.

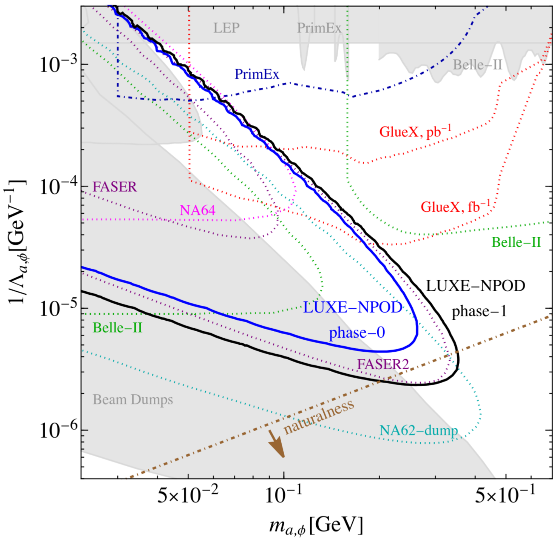

Figure 7: The result of a sensitivity study for detection of ALPs in the LUXE optical beam dump is compared to other experiments in terms of the ALP mass and coupling strength.

5. Status

Since its first conception in 2017, the LUXE collaboration now contains members from 26 institutes and has been acknowledged by DESY as aligning with their planned scientific program. After the recent publication of the technical design report [2], the collaboration foresees installation during EuXFEL shutdowns in the 2025-2026 window, with operation to follow.

6. Conclusion

LUXE is a near-future experiment using the EuXFEL electron beam together with a state-of-the-art laser system, which is poised to contribute multiple noteworthy measurements in the field of SFQED. The experiment aims to run in multiple configurations, colliding both electrons and photons with laser pulses of varying intensity and validating theoretical in an untested regime of SFQED parameter space. In its unique photon-laser collision setup, LUXE can also provide the first direct measurement of nonlinear Breit-Wheeler pair production in the non-perturbative regime using real photons, providing the most direct demonstration of the ability to create matter from the QED vacuum at high field intensities. An array of complimentary detectors aid in calibration and make it easier to perform stringent tests of SFQED in unexplored regions of the parameter space. Already far into planning & development, installation of the LUXE experiment is planned in the coming years, with data-taking to follow immediately.

7. Acknowledgements

We thank the DESY technical staff for continuous assistance and the DESY directorate for their strong support and the hospitality they extend to the non-DESY members of the collaboration. This work has benefited from computing services provided by the German National Analysis Facility (NAF) and the Swedish National Infrastructure for Computing (SNIC).

References

[1] H. Abramowicz et al., "Conceptual design report for the LUXE experiment", *Eur. Phys. J. ST* **230** (2021), no. 11, 2445–2560, doi:10.1140/epjs/s11734-021-00249-z, arXiv:2102.02032.

[2] H. Abramowicz et al., "Technical design report for the luxe experiment", *arXiv preprint arXiv:2308.00515* (2023).

[3] R. Abela et al., "XFEL: The European X-Ray Free-Electron Laser - Technical Design Report". DESY, Hamburg, 2006. doi:10.3204/DESY_06-097, ISBN 978-3-935702-17-1.

[4] E144 Collaboration, "Observation of nonlinear effects in Compton scattering", *Phys. Rev. Lett.* **76** (1996) 3116–3119, doi:10.1103/PhysRevLett.76.3116.

[5] D. L. Burke et al., "Positron production in multi - photon light by light scattering", *Phys. Rev. Lett.* **79** (1997) 1626–1629, doi:10.1103/PhysRevLett.79.1626.

[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. X* **8** (2018), no. 1, 011020, doi:10.1103/PhysRevX.8.011020, arXiv:1707.06821.

[7] K. Poder et al., "Experimental Signatures of the Quantum Nature of Radiation Reaction in the Field of an Ultraintense Laser", *Phys. Rev. X* **8** (2018), no. 3, 031004, doi:10.1103/PhysRevX.8.031004, arXiv:1709.01861.

[8] S. Meuren, "Probing strong-field qed at facet-ii (slac e-320)", in *Third conference on extremely high intensity laser physics (exhilp)*, volume 7. 2019.

[9] P. Mckenna, S. P. D. Mangles, G. Sarri, and J. Schreiber, "High field physics and qed experiments at eli-np", *Romanian reports in Physics* **68** (2016) S145.

[10] CERN NA63 Collaboration, "Precision Measurement of Trident Production in Strong Electromagnetic Fields", *Phys. Rev. Lett.* **130** (2023), no. 7, 071601, doi:10.1103/PhysRevLett.130.071601, arXiv:2211.02390.

[11] CERN NA63 Collaboration, "Differential measurement of trident production in strong electromagnetic fields", *Phys. Rev. D* **108** (2023), no. 5, 052013, doi:10.1103/PhysRevD.108.052013, arXiv:2307.03464.

[12] T. G. Blackburn, A. J. MacLeod, and B. King, "From local to nonlocal: higher fidelity simulations of photon emission in intense laser pulses", *New J. Phys.* **23** (2021), no. 8, 085008, doi:10.1088/1367-2630/ac1bf6, arXiv:2103.06673.

[13] D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses", *Opt. Commun.* **55** (1985), no. 6, 447–449, doi:10.1016/0030-4018(85)90151-8. [Erratum: Opt.Commun. 56, 219–221 (1985)].

[14] Z. Bai et al., "New physics searches with an optical dump at LUXE", *Phys. Rev. D* **106** (2022), no. 11, 115034, doi:10.1103/PhysRevD.106.115034, arXiv:2107.13554.