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LUXE — A QED EXPERIMENT AT THE EUROPEAN XFEL

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Abstract

The proposed experiment aims to measure QED in the presence of strong fields and above the Schwinger critical field. An experiment is being considered at the European XFEL, which should be able to measure non-perturbative QED and its transition from the perturbative regime. This paper presents the current status of the LUXE (Laser und XFEL Experiment) design study. First layout considerations; accelerator beam line design, electron and laser beam parameters, radioprotection issues and first results of the start to end simulations will be presented and discussed in detail. An outlook concerning the implementation into the European XFEL schedule and timeline of this experiment will be given.

INTRODUCTION

During the early phase of the development of quantum electrodynamics, Heisenberg, Euler, Schwinger and others considered a regime which has yet to be tested experimentally. This is the regime where the electromagnetic interaction becomes so strong that matter particles can be produced from the absorption of light by light. Such strong fields occur in several astrophysical phenomena, such as neutron stars, black holes and the early phase of the Universe. At DESY, a study is being conducted whether it is feasible to design an experiment called LUXE using high-energy photons, created from the electron beam of the European XFEL, and low-energy photons from a high-power laser. It is expected that electron-positron pairs are created which can be measured by dedicated detectors designed for this purpose.

The electron beam accelerator of the European XFEL, operated at DESY, is among the highest energy electron accelerators currently operating world-wide. While it was designed for the purpose of photon science it would be also ideally suited to study quantum physics in the strong-field regime. This is the goal of the LUXE experiment currently being designed by DESY accelerator, particle and laser physicists jointly with collaborators from German, Israeli and UK institutes.

The LUXE experiment foresees to shoot one of the 2700 bunches of the electron beam on a tungsten target where a high-energy photon is created through the Bremsstrahlung process. This high-energy photon then collides with low-energy photons from a laser and pairs of electrons and positrons are expected to be created, known as the Schwinger process.
The intensity of the laser is varied between 5×10^{18} W/cm^2 and 1×10^{20} W/cm^2 and the rate of electron/positron pairs is measured as function of this intensity. It is expected that this rate increases fast with laser intensity but asymptotically reaches a value directly related to the Schwinger critical field $E_S = (m_e^2 c^3)/e\hbar \approx 1.3 \times 10^{18}$ V/m. The measurement of the rate of pairs is directly related to the field: $R \propto E^2 e^{(-E_S/E)}$ where E is the electric field provided by the laser. A similar experiment was conducted at SLAC in the 1990s with the E144 experiment, where the production of electron-positron pairs was observed but the critical field was not reached [1,2].

EXPERIMENTAL SCENARIOS

For this experiment two experimental scenarios are foreseen. In the preparatory stage 1 the electron bunch is directly brought into collision with the laser pulse. In Stage 2 the electron bunch is sent onto a photoconverter foil (35 μm thick tungsten foil) and the generated photons are brought into collision with the laser pulse. Downstream of the beam transfer line from the European XFEL linac to the experimental area the experimental setup consists of an electro-magnetic triplet focussing the bunch to the interaction point (IP). For stage 1 the bunch is directly sent to the IP , whereas for stage 2 the photonconverter foil and a collimator has to be installed upstream of the IP. Downstream of the IP the spectrometer setup is located, including a spectrometer magnet to separate positrons and electrons and the corresponding detectors. The last element of the experiment will be the calorimeter setup. Electrons which have not interacted with the laser (stage 1) or photoconverter foil (stage 2) have to be guided onto a single bunch beam dump. A schematic of the two stages is shown in Fig. 1.

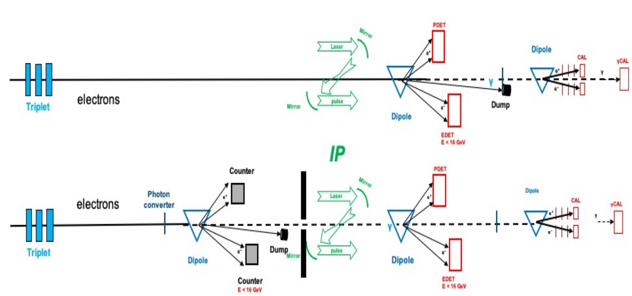

Figure 1: Experimental scenarios for the LUXE experiment. Stage 1 (top): electron bunch — laser collision, stage 2 (bottom): photon — laser collision with the photoconverter foil upstream of the Interaction Point.

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Electron Beam Parameters

For this experiment the standard European XFEL beam parameters will be used to guarantee the transparency for European XFEL user operation. The electron beam parameters are listed in Table 1:

Table 1: Electron Beam Parameters for the LUXE Experiment

	Unit	Ultimate	Nominal
Beam Energy	GeV	17.5	14
Bunch Charge	nC	1	0.25
Number of bunches	-	1	1
Repetition Rate	Hz	10	1
Spotsize at the IP	µm	5	5

LOCATION AT THE EUROPEAN XFEL

It is currently under consideration to install the LUXE experiment in the TD20 tunnel. TD20 is located in the shaft building XS1 downstream of the linac. The area with the existing beam lines T1 and T2 and the beam path to the TD20 tunnel is schematically shown in Fig. 5. The beam transport to the experiment has to be built up with an additional extraction from the linac as it has been foreseen in the design for a possible future extension of the facility with additional photon beam lines [3, 4]. A system consisting of kicker magnets and septa has to be installed at the European XFEL main beam switchyard. In this switchyard the beams are separated in TD1 and TD2 towards the undulators and to the beam dump. First lattice considerations for the extraction beam line are finished. A schematic of the lattice is shown in Fig. 3. In comparison to other possible locations at the European XFEL (e.g. at the dump cavern in XSDU1) this area has the strong benefit, that it offers more space, better accessibility and an existing basic infrastructure. Also in terms of radiation protection and background to the detectors this area is beneficial. A picture of TD20 tunnel is shown in Fig. 2. The dimensions of the tunnel are 5.4 m in width and 5 m in height.

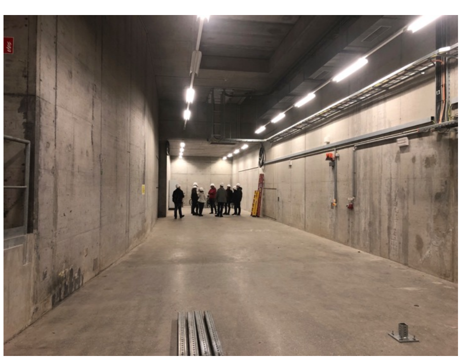

Figure 2: Picture of the TD20 tunnel. The area is equipped with a crane and a media shaft which can be used to guide the laser beam line.

Description of the TD20 Beam Line

The extraction starts with a set of fast kicker magnets [5], followed by 4 Lambertson Septa Magnets bending the beam towards the TD20 tunnel. The combination of slow kickers and fast kickers allows the extraction of single bunches with a repetition rate of up to 10 Hz to the TD20 beam line [6]. A FoDo lattice is used further downstream to guide the beam to the experimental area. A vertical chicane is used to compensate the dispersion. A triplet magnet system is used to focus the electrons down to a beam σ of 5 µm. The IP will consist of an experimental chamber, where the laser will be brought into collision with the electron bunch / photons. As the position of the laser lab and the laser beam line is under discussion, the design of the interaction point with the laser in-coupling is not yet finalised. Downstream of the interaction point the spectrometer setup, the detectors and a single bunch beam dump including the required shielding has to be placed. The total electron beam line from the first kicker magnet to the beam dump block has a length of 130 m. The beam optics of the TD20 beam line downstream of the septa magnets and the final focus were simulated with MADX and are shown in Fig. 4.

It is currently under discussion if this beam line could also serve as a test beam area after the successful completion of LUXE.

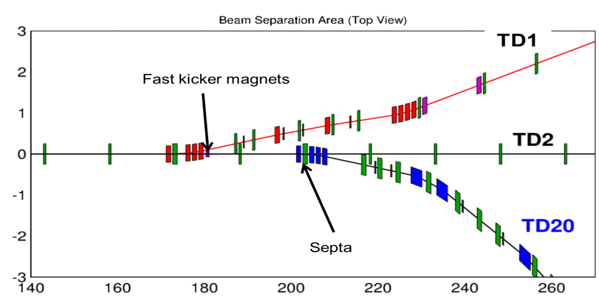

Figure 3: Lattice of the TD20 extraction beam line and the LUXE experiment. The beam line starts with the fast kicker magnets, 4 Lambertson septa magnets bend the beam towards the TD20 tunnel. Courtesy: N. Golubeva.

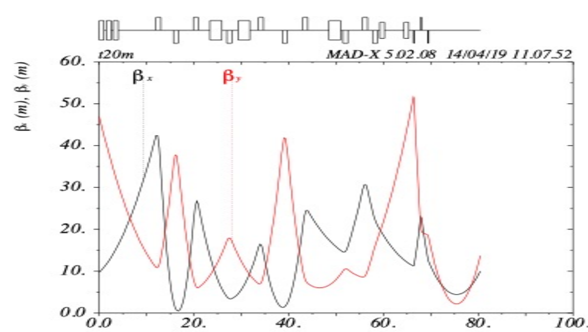

Figure 4: Beam optics simulation with MADX downstream of the septa and final focus to the experiment.

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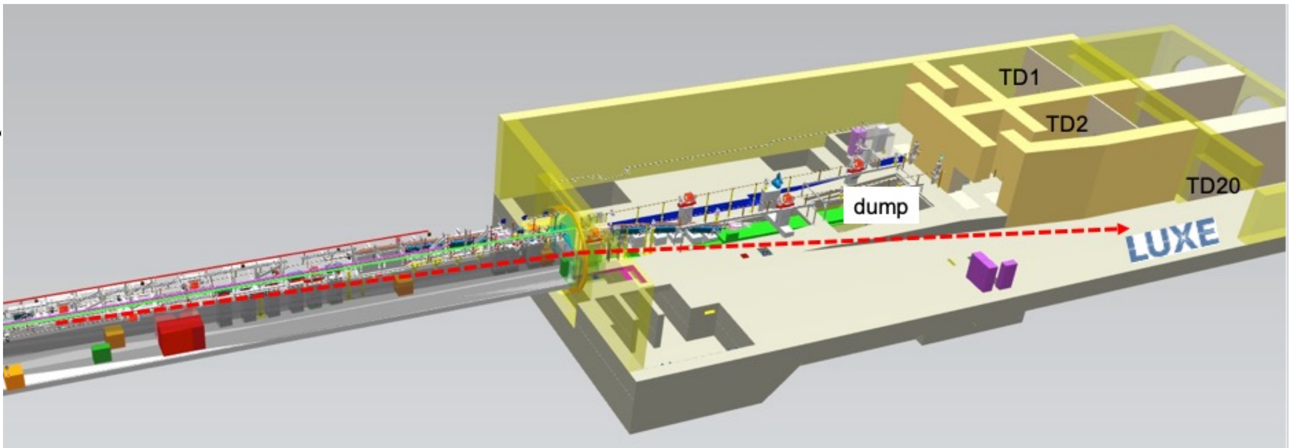

Figure 5: CAD model of the end of the European XFEL accelerator tunnel and the shaft building with the two existing beamlines T1 and T2 to the undulators and the TD20 tunnel, where the LUXE experiment will be installed. The beam extraction and the beam line towards the experiment is sketched with the dashed line.

PARTICLE DETECTORS

The detector systems for the LUXE experiment will need to meet a wide range of requirements depending on their location along the beam line and the data taking mode. The lowest occupancy is expected for the positron detectors, where only a few particles per bunch crossing needs to be detected. This can be done with existing silicon strip or pixel tracking detectors, the challenge will be to suppress backgrounds from the upstream target and collimators. The electron detectors will have to deal with several thousands or even tenthousands of particles per bunch crossing. Here, it will not be possible to reconstruct individual tracks, but only their position distribution after passing the spectrometer magnet. For this purpose, gas cherenkov detectors as developed for the Compton polarimeters of the ILC are under consideration. The biggest challenge, however, will be to perform any meaningful measurement of the photons, which can not be momentum analysed. Here, the most promising ideas comprise a thin wire-target which can scan the beam of scattered photons, and to measure the rate of charged secondaries produced.

CHALLENGES AND TIME LINE

The main goal for the LUXE experiment is to be fully transparent to the European XFEL user operation. This includes also the installation of the extraction and transfer beam line. This implies that all modifications at the European XFEL linac have to be finished within several shutdown periods (4–6 weeks). To guarantee this, a detailed modification schedule is currently under preparation with the help of the DESY technical groups. The main challenge is the modification of the support structures, magnet installation and the vacuum system in the European XFEL tunnel. First studies showed that these requirements will be met and an installation in the given time frame is feasible. After general agreement by the European XFEL management and council the timeline foresees that funding will be seeked end of 2019. The construction could start with the goal of first beam extraction earliest in 2022 as the modifications, production and procurement will require an intense preparation phase.

CONCLUSION

LUXE would be a QED basic research experiment enlarging the scientific scope of the European XFEL. The theory and accelerator community is interested to conduct this experiment at the European XFEL. First design considerations were started with the input of the DESY technical groups and the European XFEL operation group. The achievable parameters, the layout and the location in the TD20 tunnel look feasible. The modifications, mainly installation of an additional extraction at the European XFEL linac is currently being studied. The construction would be the early implementation of the beam extraction for a possible future European XFEL upgrade. First installation work is foreseen in 2021.

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