Study of QED in Strong Field Regime at LUXE Experiment

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LUXE – Laser Und XFEL Experiment

- Introduction
- Design of experimental setup at European XFEL
- Observables study in MC simulations
- Summary and plans
Strong Field QFT

- In a presence of strong electromagnetic field, the virtual charges, start to separate.
- In the Schwinger limit, an electric field ($\varepsilon_s = 1.3 \times 10^{18}\text{V/m}$) does the work equivalent to separating two electron rest masses over a Compton wavelength

$$\frac{\hbar}{m c} e \varepsilon \geq m c^2$$

$$\varepsilon_s = \frac{m^2 c^3}{\hbar e}$$

- Vacuum state becomes unstable and the field is predicted to induce vacuum pair production.

Fields reach the Schwinger limit:
- in e+e- collisions;
- in heavy ion collisions;
- in an astrophysical setting near the surface of a magnetar.

High power laser facilities provide a possibility to study strong field QED in clean lab conditions.

LUXE is intended to use European XFEL e- beam and high power laser to probe strong field QED.
Laser-assisted pair production

\[ \gamma + n\omega \rightarrow e^+e^- \]

One photon pair production (OPPP) at ultra high intensity - non-perturbative physics

The rate of laser-assisted (OPPP) rate:

\[ \Gamma_{\text{OPPP}} = \frac{\alpha m_e^2}{4 \omega_i} F_\gamma(\xi, \chi_\gamma) \]

\[ \xi \equiv \frac{e |E|}{\omega m_e} = \frac{m_e |E|}{\omega E_c} \]

\[ \chi_\gamma \equiv \frac{k \cdot k_i}{m_e^2} \xi = (1 + \cos \theta) \frac{\omega_i}{m_e} \frac{|E|}{E_c} \]

Use bremsstrahlung photons produced by XFEL beam hitting tungsten target.

\[ \Gamma_{\text{BPPP}} = \frac{\alpha m_e^2}{4} \int_0^{E_e} \frac{d\omega_i}{\omega_i} \frac{dN_\gamma}{d\omega_i} F_\gamma(\xi, \chi_\gamma(\omega_i)) \]

\[ \Gamma_{\text{BPPP}} \rightarrow \frac{\alpha m_e^2}{E_e} \frac{9}{128} \sqrt{\frac{3}{2}} \frac{X^2}{X_0} e^{-\frac{8}{3}} \left(1-\frac{1}{15\xi^2}\right) \frac{X}{X_0} \]

Low-energy photons from laser

High-energy (relativistic) photon

High Intensity Compton Scattering

\[ e^- + n\omega \rightarrow e^- + \gamma \]

The rate of High Intensity Compton Scattering (HICS) is proportional to:

\[ \sum_n \delta^{(4)} \left[ p_i + k \frac{\xi^3}{2\chi_i} + nk - p_f - k \frac{\xi^3}{2\chi_f} - k_f \right] \]

Momentum conservation is a sum over external field photon contributions, \( nk \)

Even for \( n=0 \) there is an irreducible contribution:

\[ p_i + k \frac{\xi^3}{2\chi_i} \rightarrow p_i^2 = m^2 (1 + \xi^2) \]

• Strong field leads to increase in electron rest mass.
• Observation of Compton edge shift.
The European XFEL is a research facility producing high-energy X-ray light for various studies; under operation since 2017; maximum electron beam energy so far: 17.58 GeV, (prediction based on accelerator module test facility is 19.3 GeV).
Electron and laser beam parameters

European XFEL electron beam:
- Electron beam parameters are defined by European XFEL LINAC;
- Energy 17.5 GeV (also possible 10 GeV and 14 GeV);
- Normalized emittance 1.4 mm mrad;
- Repetition rate 10 Hz.

Laser:
- Laser wavelength = 800.00 nm (1.5498 eV);
- Circular polarized;
- Power:
  - Stage 0: \( 10^{19} \text{ W/cm}^2 \), \( (0.35 \text{J}, \text{100 } \mu\text{m}^2, 35 \text{ fs}, \xi = 1.5, \chi = 0.3) \);
  - Stage 1: \( 2 \times 10^{20} \text{ W/cm}^2 \), \( (7.0 \text{J}, \text{100 } \mu\text{m}^2, 35 \text{ fs}, \xi = 6.8, \chi = 1.4) \);

<table>
<thead>
<tr>
<th>E_pulse, J</th>
<th>Crossing angle, rad</th>
<th>Laser ( \sigma_{xy} ), ( \mu\text{m} )</th>
<th>Laser ( \sigma_z ), ps</th>
<th>N Electrons</th>
<th>Electron ( \sigma_x ), ( \mu\text{m} )</th>
<th>Electron ( \sigma_y ), ( \mu\text{m} )</th>
<th>Electron ( \sigma_z ), ps</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5</td>
<td>0.3</td>
<td>10</td>
<td>0.035</td>
<td>6.25E+09</td>
<td>5.0</td>
<td>5.0</td>
<td>0.08</td>
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</tbody>
</table>
LUXE Setup

Photon-Photon collisions at LUXE

Electron-Photon collisions at LUXE
Bremsstrahlung production (complete screening, thin target):

\[
\omega_i \frac{dN_\gamma}{d\omega_i} \approx \left[ \frac{4}{3} - \frac{4}{3} \left( \frac{\omega_i}{E_e} \right) + \left( \frac{\omega_i}{E_e} \right)^2 \right] \frac{X}{X_0}
\]

- Gaussian beam;
- Tungsten target 1%X0 (35µm), 2m from IP;
- Two histograms are compared:
  - \(|x| < 1\text{mm} \text{ and } |y| < 1\text{mm} \) (red);
  - \(|x| < 25\mu\text{m} \text{ and } |y| < 25\mu\text{m} \) (green).

- Electrons and positrons observed in forward area behind the target (θ<17°) for one BX.

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<table>
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<tbody>
<tr>
<td>(N_e^-)</td>
<td>6.26E+09</td>
</tr>
<tr>
<td>(N_{e^-, &lt; 16\text{ GeV}})</td>
<td>1.80E+08</td>
</tr>
<tr>
<td>(N_{e^+})</td>
<td>1.62E+06</td>
</tr>
</tbody>
</table>

- Can be measured to monitor number of photons.
Target Thickness and Angular Distribution

- Gaussian beam;
- Tungsten target 5m from IP;
- Photons selection:
  - $|x| < 25 \mu m$ and $|y| < 25 \mu m$;
  - $E > 7 \text{ GeV}$.

<table>
<thead>
<tr>
<th>$N_\gamma$</th>
<th>$4.91 \times 10^6$</th>
</tr>
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<tbody>
<tr>
<td>$N_\gamma, E &gt; 7 \text{ GeV}$</td>
<td>$4.66 \times 10^5$</td>
</tr>
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</table>

For a distance $R$ between target and IP:

$$N_\gamma(R) = \frac{R_0^2}{R^2} N_\gamma(R_0)$$

Angular and spacial distribution of bremsstrahlung photons at LUXE IP
Full SQED calculations in a pulse can be challenging, so approximations are attractive.

Locally constant field approx (LCFA) assumes $\xi \gg 1$. Not appropriate for LUXE.

Laser pulse contains approximately 12 wavelengths, it makes infinite plane wave (IPW) approximation suitable for LUXE and well understood Volkov solutions can be employed.

The local intensity of the laser pulse along with the 4-momenta of initial states are used in a Monte-Carlo of the SQED transition rate.

One Photon Pair Production in MC

- The rate is up to ~100 e-e+ pairs per one bunch-laser interaction;
- The energy spectra peak at 7 GeV;
- Spectrometer:
  - 1.4T magnet of 1m length;
  - Pixel detector (100 x 100 µm² pixel) located 1m away from the magnet;
  - Detection efficiency ~99%.
- Background and energy resolution to be studied!

OPPP rate

OPPP e-, e+ spectra

Average occupancy of spectrometer detectors
Photon-Photon collisions at LUXE

- Bremsstrahlung production monitor (section B): Cherenkov counters and calorimeters;
- OPPPP measurements (section D): spectrometer (dipole + few layers of tracking detectors) and calorimeters;
- Forward detector (section E): low X0 target, spectrometer (dipole + few layers of tracking detectors), Cherenkov counters and calorimeters;
- γCAL: calorimeter capable of handling high photon flux.
Electron-Photon collisions at LUXE

MC simulation with $6 \times 10^9$ electrons per bunch;

Electron and photon spectra for 0.6J laser

<table>
<thead>
<tr>
<th>Laser Power, J</th>
<th>Number of e- E &lt; 16 GeV</th>
<th>Number of γ</th>
</tr>
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<tbody>
<tr>
<td>0.6</td>
<td>2.18E+09</td>
<td>5.74E+09</td>
</tr>
<tr>
<td>0.2</td>
<td>1.16E+09</td>
<td>2.31E+09</td>
</tr>
<tr>
<td>0.1</td>
<td>6.82E+08</td>
<td>1.24E+09</td>
</tr>
<tr>
<td>0.01</td>
<td>8.47E+07</td>
<td>1.35E+08</td>
</tr>
</tbody>
</table>

- Electron detection: dipole with Cherenkov counters;
- Trident positron detection (~0.1 per BX at 0.6J observed): spectrometer (dipole + few layers of tracking detectors) and calorimeter.
- Forward detector: low X0 target, spectrometer (dipole + few layers of tracking detectors), Cherenkov counters and calorimeters;
- γCAL: calorimeter capable of handling high photon flux.
Observation of Kinematic Edges

- Kinematic edges are smeared because of the intensity distribution in the laser pulse;
- The effect is stronger for higher intensities;
- For low intensities the edges are well pronounced and measurable;
- For $\xi=0.26$ the edge is at 4.6 GeV while Compton edge would be at 5.3 GeV;
- 3D distributions of MC shows the spectra at instant intensity.
Active Wire Target for Forward Photon Detector

- Wire target of few microns thickness has $\sim(10^{-3} - 10^{-4}) \times 0$;
- Technology is available and was used in the past;
- It selects small ($\sim 10^{-3} - 10^{-4}$) fraction of the photon flux because of its angular distribution;
- Produced number of pairs would be in the range ($\sim 10^{-2} - 10^{-3}$) It is manageable number for the spectrometer with pixel detectors.
- Secondary electron emission (SSE) from the wire can be measured providing additional information about the photon flux.

Simulation with 10µm tungsten wire

Projected 1D photon distribution 10m from IP.
Summary

- LUXE at DESY proposes to extend scientific scope of European XFEL to probe fundamental physics in new regime of strong fields.
- Experimental study of laser assisted pair production and high intensity Compton scattering is feasible with European XFEL beam.
- Conceptual design study of LUXE experimental setup shows that the detector subsystems can be built using existing technologies for magnets, pixel tracking detectors, Cherenkov counters.
- Ongoing work on detailed background simulation and reconstruction algorithms development.
- Though the required lasers are available from the industry the technique and tools for their accurate power monitor need to be developed.