Compton process and measurement

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1 Introduction

The proposed experiment LUXE (Laser und XFEL Experiment) aims for studying non-perturbative QED processes in collisions of European XFEL electron beam and terawatt laser pulse. Here we report on the possibility of observation nonlinear High Intensity Compton Scattering in the LUXE experiment focusing on conceptual forward photon detector design study in GEANT4 simulation.

2 Nonlinear Compton scattering

With terawatt lasers it is possible to create a sufficient photon density to study nonlinear Compton scattering (or High Intensity Compton Scattering (HICS)). An electron in the intense wave may radiate a photon and balance 4-momentum by absorbing multiple photons from the laser, which can lead to real photons with energies above the kinematic limit for conventional Compton scattering. In this process an electron absorbs multiple photons from the laser pulse, and radiates a high energy photon:

$$e^- + n\omega \rightarrow e^- + \gamma, \tag{1}$$

where ω represents the photon from the laser pulse, n the number of absorbed laser photons and γ is high energy photon. The rate of this process depends on the laser intensity parameter

$$\xi = \frac{eE_L}{\omega_L m_e} \tag{2}$$

where E_L and ω_L are the laser electric field and its frequency in the electron-laser rest frame, respectively, and e and m_e are the electron charge and mass.

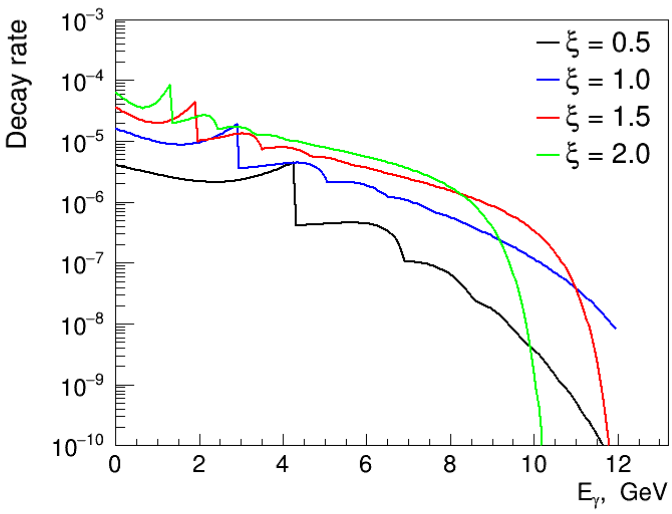
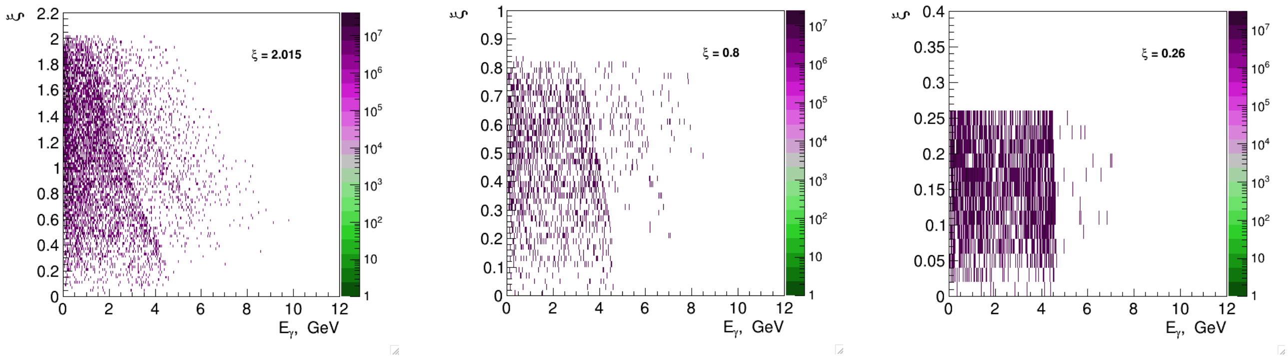


Figure 1: Analytic decay rates of HICS for different laser intensities for LUXE.

Photons scattered to energies higher than the kinematic edge of order n can only be due to nonlinear HICS, (1). As n increases, the scattered photon can reach higher energy and the yield decreases. The solid curves in Fig. 1 are the analytical overall spectra of scattered photons, including all orders of n. Two effects are observed. First, the photon spectrum of the HICS process exhibits a series of visible Compton edges related to multiphoton contributions from the external field. The kinematic edges between different orders become less distinguishable as n increases. Second, each Compton edge is shifted by an amount proportional to the laser intensity. The shift moves toward the lower energies as the field increases because of increase of effective electron mass []. To model HICS process in the conditions of real experiment Monte Carlo (MC) is used. The MC for the LUXE experiment reproduces non perturbative, strong field particle processes in the collision between an electron bunch and an intense laser pulse. The modelling provides the propagation and detection of the colliding beams, and also the physics at the interaction point (IP) itself. The MC modelling of HICS process is described in detail in [Hartin]. For the simulation a circularly polarised laser beam with wavelength 800 nm and crossing angle of 17.2 degrees is used. The focal-spot area is 100.0 μm^2 and the pulse length is 35 fs assumed to be flat in transverse direction and Gaussian in longitudinal with $\sigma_z = 12\ \mu m$. The electron bunch has a Gaussian distribution and contains of $6 * 10^9$ incident electrons distributed with $\sigma_x = \sigma_y = 5\ \mu m$ and $\sigma_z = 24\ \mu m$. Three laser intensities were considered 0.01, 0.1 or 0.6 J (or expressed in ξ : 2.02, 0.80 and 0.26).

Figure 2 shows the distributions of photon energy E_γ versus instant local laser intensities ξ at production point. For the highest peak intensity 2(a) the kinematic edges with $n > 1$ could be seen as shade transition lines for different values of ξ. But experimentally only the projection to the horizontal axis can be measured. In this case for the highest modelled intensity 2(a) the kinematic edge will be smeared and hardly visible in final photon spectrum because of non-uniform laser intensity. For the lower peak intensities 2(b), 2(c) the kinematic edges can be observed and measured. The Figure 3 shows the projection 2(c) to the x axis. One could see the profound and well visible kinematic edges from n = 1 and n = 2 contributions. The mass shift could be studied at low intensity, which is easier to see experimentally. As it could be seen in Figure 3 the first kinematic edge is shifted approximately by about 500 MeV compared to Copmton edge of $\sim$ 5.3 GeV at ξ= 0.26 (0.01 J laser pulse energy). Also the second kinematic edge could be measured which is a subject of higher statistics.



a) b) c)

Figure 2: Distributions of photon energy E_γ versus instant laser intensities at production point, which correspond to peak laser intensities $\xi = 2.02$ (a), $\xi = 0.80$ (b) and $\xi = 0.26$ (c).

The rate of reaction (1) estimated from MC ranges from 10^9 for the peak laser intensity of ξ= 0.5 to 10^{11} for ξ= 2.0 during each laser pulse, which makes the registration and spectra measurement the challenging task. This also precludes a coincidence measurement of the two final state particles from a single interaction.

3 Forward Detector System

In the present study the conceptual design of Forward Detector System (FSD) implemented in simulation includes a conversion target, spectrometer which consists of dipole magnet, tracking detectors and electromagnetic calorimeters. The forward-going photons produced at IP are either travel to a thin target in which a small fraction would convert into electron-positron pairs, or to a monitor of the total rate. In the former case, the electrons/positrons enter FDS consisting of a dipole magnet and 3 tracking planes to measure the particle tracks, as shown in Fig. 4 which presents the schema of experiment that was studied in GEANT4. The target was located in the centre on a distance of 10 m from IP. Magnet parameters were chosen to be compatible

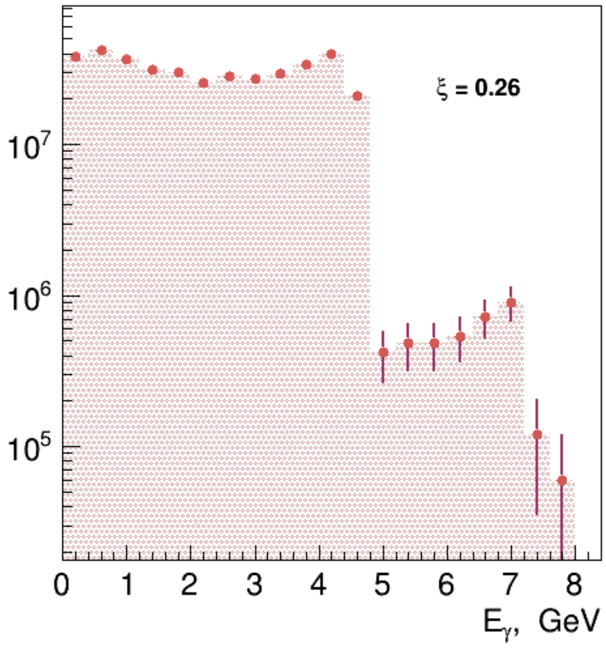


Figure 3: Photon energy distributions in MC for the peak laser intensities of $\xi = 0.26$

with devices at DESY with the thickness of 1m and field up 2 Tesla. Tracking detectors were represented as pixel counters. The forward photon spectrum could be inferred from electron/positron momentum spectrum via convolution with the Bethe-Heitler pair production spectrum. The total number of back-scattered photons, dominated by the linear Compton scattering process, is measured at the end of the beamline by the silicon-tungsten calorimeter GCAL (LumiCal). At the expected laser intensities with high energy photons incident on

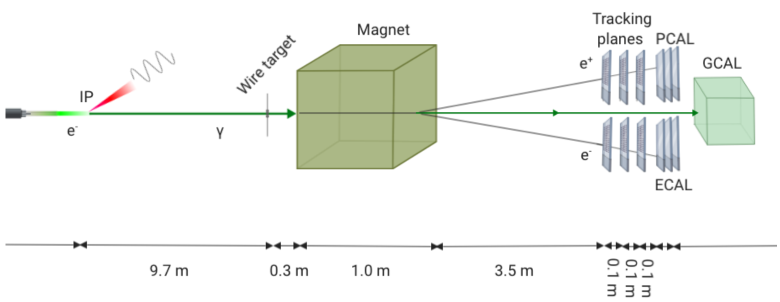


Figure 4: Schematic of the FDS.

a X_0 thick target, $\sim 10^8 - 10^9$ e^+e^- pairs would enter the pair spectrometer in each laser pulse. Most of these are produced by photons in the linear (n = 1) portion of the Compton spectrum. To combat the high photon fluxes produced after IP the thin metal wires as conversion detectors positioned on some substantial distance from IP could be used. The Fig. (5) shows the projected photon distribution produced for laser energy of 0.6 J in a transverse plane 10 m away from IP. The area selected by the green lines represents the wire of 10 μm. By sampling small fraction of the beam using low X_0 target we can achieve the numbers of e^+e^- which can be measured by pixel detectors of existing technology. Moving the wire one could study the angular distribution of HICS.

The focus of this simulation study is the estimation the number of pairs depending on the material and detector target.

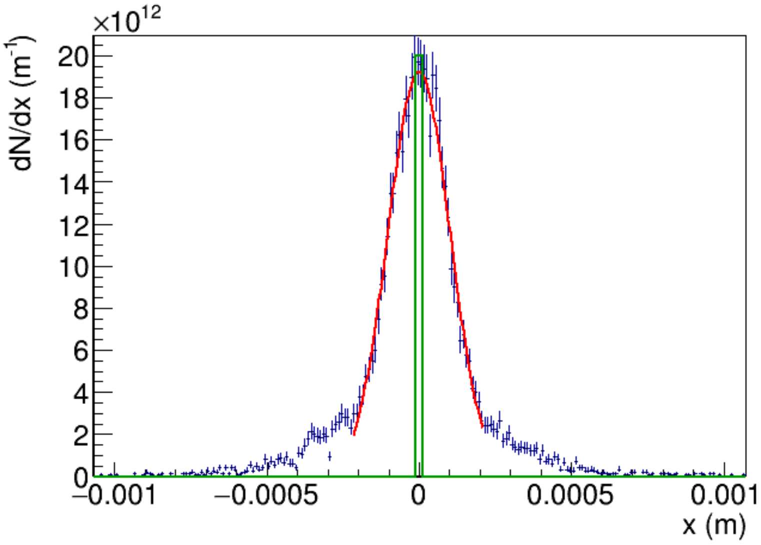
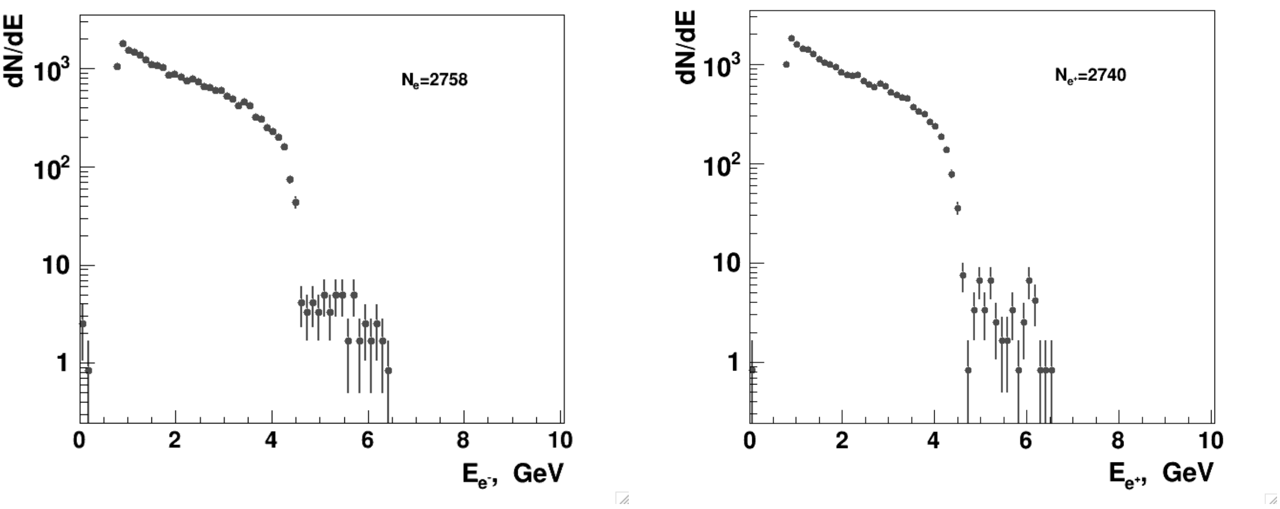


Figure 5: Projection of the photon distribution on a distance 10 m from IP.

3.1 Simulation Results

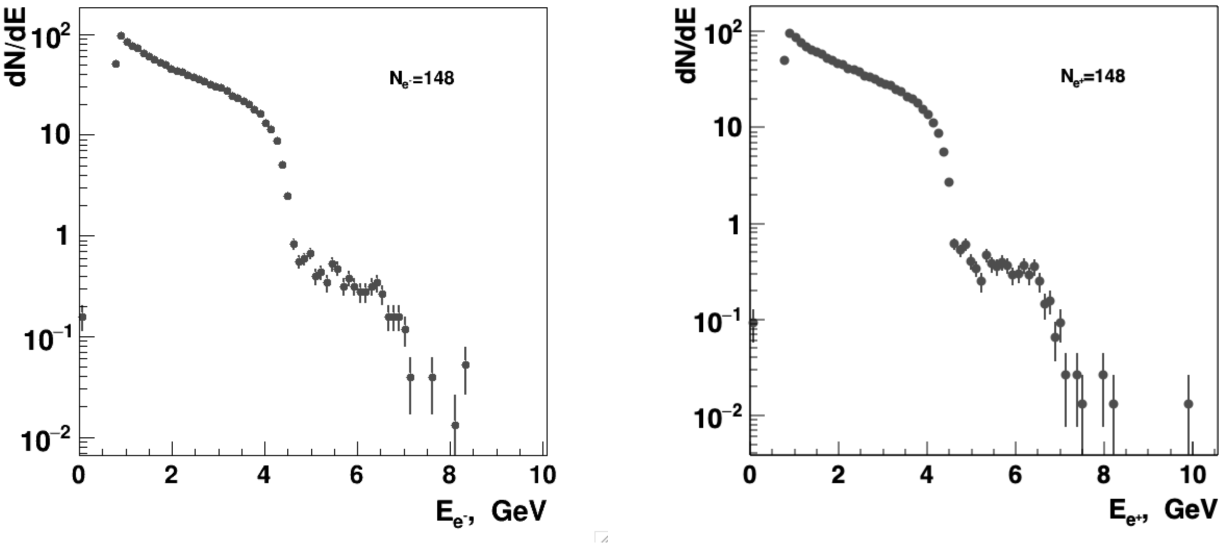
The simulation is performed in GEANT4 [?] framework to study the performance of the LUXE forward photon detector system with a target to convert photons to e^+e^- pairs. The geometry and output settings match the LUXE preliminary design and needs. In the code the input for the primary particles can be read from the list in external file with arbitrary settings for particle type, momentum and position. In FDS case it is an output from the simulation of electron – laser interaction which contains photons produced in high intensity Compton scattering. Preliminary studies in simulation of the feasibility of usage 10 μm tungsten (W, density: 19.3 g/cm^3) wire as converter target showed that for the nominal XFEL beam with peak laser intensity of $\xi = 0.26$, on a distance of 10 m from IP, the number of expected electron/positron pairs is $\sim 2.7 * 10^3$. The electron/positron spectra for 1000 BX are shown in Fig. 6. First two kinematic edges are well visible. Also the simulations for 1 μm and 5 μm W wires were performed and the expected numbers of pairs are found to be around ∼670 and 24, respectively.



a) b)

Figure 6: Electron (a) and positron (b) spectra for Tungsten wire convector which correspond to peak laser intensity of $\xi = 0.26$.

Another material that was studied as a wire converter is Nickel (density: 8.9 g/cm^3). In a run with 10^8 photons distributed according to MC (Fig. 3) that hit the 10 μm Ni wire on the distance of $\sim 10m$ from IP, the number of produced pairs is 150 (ξ=0.26). These moderate numbers give a possibility of proper particle reconstruction and maybe the identification of the positron partner for a given electron. (?)



a) b)

Figure 7: Electron (a) and positron (b) spectra for Nickel wire which correspond to peak laser intensity $\xi = 0.26$.

Another question about the thin targets is their thermo-stability in the LUXE experimental conditions. The thermal expansion, as a result of the energy deposition, is associated with mechanical tension. The average deposition per particle pass dE/dx could be obtained from GEANT simulation. Using this value and the geometry of wire one can estimate the thermal damage by photon passage through a thin target. The total energy deposit in 1 μm thick Ni-wire per event is $4 * 10^{-4}\ eV$, in 10 μm – 3.2 eV. The beam dissipated power in 1 μm thick Ni-wire can be easily extracted via radiation. The wire of about $10^{-4}\ m^2$ in area with > 0.1 absorption coefficient will stay at 40 $°C$ in an ambient vacuum system of 40 $°C$ chamber temperature. More study is need.

In addition the technology of production $\sim$ 1.0 micrometer thick radiation hard micro-strip detectors (MSD) could be employed. MSD were designed for non-destructive online measurements of radiation beam parameters and developed at the Institute for Nuclear Research NASU for the beam profile monitoring of the synchrotron radiation as well as for the charged particles beam profile monitoring []. The current technology allows for production of the thin (down to $\sim$ 1 μm) Ni-strips with a pitch of about few micrometers, providing high position resolution. The principle of MMD operation is based on the phenomenon of Secondary Electron Emission (SEE)[1]. Beam of charged particles or photons passing through the thin strip initiates SEE resulting in thereby a positive charge. The charge could be measured by high-sensitivity charge integrator connected to the strip. Collecting the charge will provide the information about the passing particle flux.

3.2 Forward photons

The original HICS photon spectra can be reconstructed using the convolution of the simulated photon spectrum with the Bethe-Heitler pair spectrum. For this purpose the model parametrised spectra of HICS photons can be convoluted with Bethe-Heitler pair spectrum and fit to experimentally observed e^+ / e^- spectra. Fig. 8 shows the result of such a fit, where the cross-section of pair production in target material was obtained from GEANT4 and a simple step function was used to model HICS photon spectrum. As it can be seen from Fig. 8 the fit rather well reproduces the spectrum of electrons and the kinematic edges of 4.65 GeV for n=1 and 7.17 GeV for n=2 were obtained.

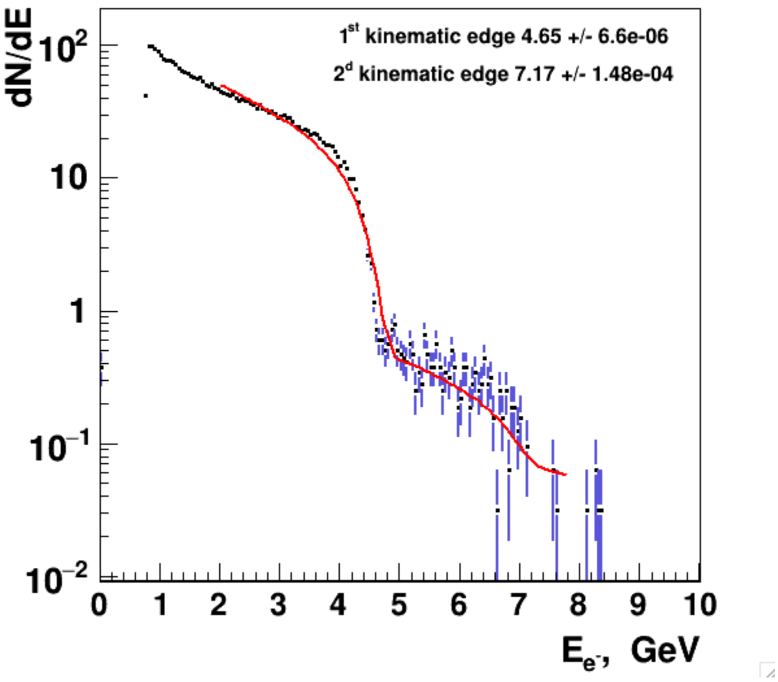


Figure 8: Electron spectrum from conversion of forward photons. The red line is a fit to the simulation data

4 Summary

A GEANT4 application has been developed to simulate Nonlinear Compton Scattering in collisions of an XFEL electron beam with terrawatt laser pulse for the LUXE experiment. HICS could be studied either by observing forward high-energy photons or by measuring the scattered electrons. We present the results of Bethe-Heitler conversion of Compton photons on metal target to produce e^+e^- pairs.

The average number of pairs for a Nickel target of 10 μm thickness and $\sim 6 * 10^4$ bunches crossing of XFEL electron beam is ~ 150.