Detector requirements for a future experiment based on a high-energy electron beam and high-power laser

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The following is an outline of the particle properties in proposed strong QED experiments with high-energy electron beams; this is to provoke discussion of the detectors needed. The initial beams are first described. It explains the properties of the final-state electrons, positrons and photons produced in the collision of a high-energy electron bunch and a high-power laser pulse. Interaction points for electron–laser (i.e. $e\gamma$) and also $\gamma\gamma$ are assumed to be possible. Initial thoughts on the constraints and issues this places on the detectors are also outlined.

Initial beams

Initial electron bunches are assumed to be like those found at EU.XFEL (LUXE) and SLAC (LCLS/FACET-II) and approximate values of relevant parameters are:

- an electron energy, $5 < E_e < 20\,\text{GeV}$;
- a bunch charge of $N_e = 10^8 - 10^{10}$ electrons;
- a bunch length of $\sigma_z \sim$ few $- 100\,\mu$m;
- the repetition rate will be dictated by the laser frequency;
- a beam size of $\sigma_{x,y} \sim$ few $- 50\,\mu$m, although maybe this is not so relevant for the detector requirements.

The high-power laser is assumed to have the following properties:

- a $\sim 100\,\text{TW}$ [$\sim 1\,\text{PW}$] laser system, e.g. $\sim 2.5\,\text{J}$ [$\sim 25\,\text{J}$] in $\sim 25\,\text{fs}$;
- a typical focal area of $(10\,\mu\text{m})^2$, implying an intensity of $10^{20}\,\text{W}\,\text{cm}^{-2}$ [$10^{21}\,\text{W}\,\text{cm}^{-2}$];
- the laser is most likely a Ti:sapphire system (800 nm central wavelength, i.e. typical photon energy: 1.55 eV);
- this implies a reduced vector potential of $a_0 = \xi \approx 5$ [$a_0 = \xi \approx 15$] and a quantum parameter of $\chi = \Upsilon \approx 0.6$ [$\chi = \Upsilon \approx 1.8$] for head-on collisions with a 10 GeV electron/photon[1] ;

[1] The properties of strong-field QED processes in a laser pulse with photon energy $\hbar\omega_L$ and electric field strength E are mainly determined by two gauge and Lorentz invariant parameters [1],

$$\chi = \Upsilon = \frac{2\epsilon}{mc^2}\frac{E}{E_{\text{cr}}} \approx 0.5741\,\frac{\epsilon}{\text{GeV}}\sqrt{\frac{I}{10^{22}\,[\text{W}\,\text{cm}^{-2}]}}, \quad \xi = a_0 = \frac{eE}{mc\omega_L} \approx 0.7495\,\frac{\text{eV}}{\hbar\omega_L}\sqrt{\frac{I}{10^{18}\,[\text{W}\,\text{cm}^{-2}]}}.$$

- the repetition rate will be in the range $0.1 - 10\,\mathrm{Hz}$;
- the laser is linearly polarised (full control of the polarisation, i.e. linear over elliptical to circular possible), thus there is the possibility of producing polarised photons and electrons and positrons;
- near backscattering with electron and/or gamma beam;
- some level of frequency conversion and longitudinal pulse shaping will be available at reduced intensities.

Final-state particle properties and detectors

Photons

At E144, up to 10^7 photons were produced per electron bunch–laser pulse interaction. The electron bunch population for future experiments will be similar to E144, but with the significant increase in laser intensity, we expect something like

- up to $\sim 10^{11}$ photons, i.e. up to 10 photons per incident electron;
- the transverse size of the photon bunch at the interaction point will be about $10\,\mu$m, i.e. $<$ mm for $\mathcal{O}\,(10\,\mathrm{m})$ downstream (can change with different emittance of electron beam);
- typical energy will be $1 - 10\,\mathrm{GeV}$.

Ideally, we would like to measure the number of photons (and electrons and positrons too) and the energy spectrum. However, we will need to measure the integrated signal when there is no chance of measuring all individual photons. Alternatively, one could e.g. reduce the number of initial electrons and so produce fewer photons if needed. Is a system with a foil to convert the photons to an electron–positron pair useful ?

Electrons

The final-state electrons consist of three different populations: a) electrons which have never or at most radiated soft photons (nearly unchanged from the initial electrons); b) electrons which have radiated a hard photon (energy losses up to 99% are feasible); c) electrons which are produced via photon decay into electron–positron pairs (total energy $\gtrsim 1\,\mathrm{GeV}$, due to threshold). Furthermore, the electrons differ in transverse momentum, which is induced by the laser. Due to the Lawson-Woodward theorem the final state of population a) is nearly unchanged. Electrons from population b) and c) exhibit a transverse momentum of $\sim 5\,\mathrm{MeV}$ along the laser polarisation direction and $\sim 0.5\,\mathrm{MeV}$ along the orthogonal direction

where $e > 0$ denotes the elementary charge, m the electron/positron mass and $E_{\mathrm{cr}} = m^2c^3/(e\hbar) \approx 1.3 \times 10^{18}\,\mathrm{V\,m^{-1}}$, the QED critical field. The expression given for χ holds only for a head-on collision of an (ultra-relativistic) electron/positron or photon with energy ϵ (see [1] for a general discussion).

(for circular polarisation there is no preferred direction and the transverse momentum is of order 5 MeV everywhere).

We expect in $e\gamma$ collisions:

- $\sim 10^{10}$ electrons, i.e. one electron per incident electron;
- the electrons will be separated from the positrons and will also have some spread due a magnetic spectrometer;
- typical energy will be $1 - 10$ GeV.

This provides a cross-check of the photon signal (and vice-versa). Could we use the same type of detector for electrons and photons ? Would this be a calorimeter or (silicon) tracker or a combination of both ? To what extent does a magnetic spectrometer simplify the system ? We would like to distinguish the electrons in pair production from those in Compton scattering.

Positrons

The number of electron–positron pairs depends strongly on the input parameters such as the laser pulse length and Lorentz invariants that characterise the strong-field interaction. At low fields, an electron–positron pair will be produced per bunch crossing. At higher fields, up to 0.1 electron–positron pairs are expected per incident e/γ. We expect:

- $1 - 10^9$ positrons, i.e. up to 0.1 electron–positron pair per incident electron;
- the positrons will be separated from the electrons and will also have some spread due a magnetic spectrometer;
- typical energy will be $1 - 10$ GeV.

So we would go from a scenario of producing low numbers of pairs where we would want to measure both the e^+ and e^- separately and correlate them. Then at much higher rates, we would need to sum as above for electrons and photons in the $e\gamma$ reaction. Can we have a detector that can do both ? What resolution is required to be able to associate pairs ? Is timing important ?

[1] A. Di Piazza, C. Müller, K.Z. Hatsagortsyan and C.H. Keitel, "Extremely high-intensity laser interactions with fundamental quantum systems", Rev. Mod. Phys. **84** (2012) 1177.

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