draft, dated August 8, 2013

HIBEF:
Strong-Field Physics Probed by the XFEL[1]

1 Executive summary

The XFEL combined with an optical petawatt laser system offers unprecedented opportunities for the investigation of the polarization of the quantum vacuum, searching for signatures of the Unruh effect, searching for new particles beyond the Standard Model, pair creation, Compton and trident processes. Among the key issues of strong-field physics are "vacuum birefringence", apparent temperature shift of an accelerated expanding plasma mimicking gravity effects and the search for new particles with great scientific potential for a number of break-through experiments. These will open new avenues toward an exploration of hitherto uncharted non-linear effects in the interaction of light and charged particles.

2 Prelude: Strong fields

For many processes in electromagnetic (e.m.) fields, the classical intensity parameter a_0 delineates the weak-field region $a_0 < 1$ from the strong-field region $a_0 > 1$ with the meaning that, in the latter regime, an electron with mass m and charge e becomes relativistic even if initially at rest. In that regime, the electron's dynamics is highly nonlinear in the field amplitude. To be specific, for a laser e.m. field characterized by the peak intensity I and frequency ω, one has $a_0 = 7.5\sqrt{\frac{I}{10^{20}\mathrm{W/cm^2}}\frac{eV}{\omega}}$. While a_0 refers solely to the external e.m. field with field strength tensor $F_{\mu\nu}$, the quantum parameter $\chi = \frac{e}{m^3}\sqrt{-(F_{\mu\nu}p^\mu)^2}$ indicates the importance of quantum effects; the latter one can be severe for $\chi > 1$ (here, p^μ is the four-momentum of particles/photons involved in the respective process).
In the strong-field regime, new, nonlinear processes are facilitated, related to multi-photon and tunneling phenomena as well as to properties of the quantum vacuum. All these depend sensibly on the structure and the particle content of the governing theory, that is quantum electrodynamics (QED) or other pillars of the Standard Model of particle physics. The status of the knowledge and challenges of strong-field physics is reviewed recently in several publications [1, 2, 3, 4]. For a covariant and gauge invariant formulation

[1]For previous material see D. Seipt, T. Nousch, B. Kämpfer, XFEL HGF Beam Line, Strong-Field Part (dated April 5, 2012), HZDR - Hadron Physics home page.

of a_0 as well as its interpretation see [5]; $1/a_0$ is the analog of thr Keldysh parameter in atomic physics.
Despite of the coherence properties and the high intensity of XFEL, due to the high energy of photons, $\omega_{XFEL} = 3 \cdots 15$ keV, its photon beam is characterized by $a_0^{XFEL} < 10^{-2}$. In contrast, an optical petawatt laser (PWL) achieves $a_0^{PWL} = 10 \cdots 100$ depending on actual power and focusing. Therefore, the XFEL is considered in many of the below described experiments as probe photon beam, and the strong e.m. field is provided by the petawatt laser.
An electron beam is presently not foreseen within the HIBEF-XFEL facilities (SASE-2 station). However, on the mid/long-term a moderately relativistic electron beam is discussed in the context of a THz source [6]. In addition, accelerated electrons or positrons driven by the PWL in the sub-GeV range [7] present an option for experiments with relativistic particle beams with such forthcoming additional tabletop installations.
This chapter describes a few potentially flagship experiments enabled by the XFEL + PWL constellation.

3 Experimental prospects and proposals for HIBEF at XFEL

The HIBEF at XFEL opportunities have been discussed[2] in the Strong-Field working group during the Kickoff Meeting for the Helmholtz International Beamline for Extreme Fields (HIBEF) at the European XFEL, DESY/Hamburg, June 2nd- 5th, 2013.[3] In a series of oral presentations[4] experimental proposals and their feasibilities as well as principal aspects were considered. This section summarizes the contributions with respect to realizations at HIBEF. These uncover the key issues of polarization of the quantum vacuum, signatures oft the Unruh effect, searching for new particles beyond the Standard Model, pair creation, Compton and trident processes. Some of the interesting physics cases made during the HIBEF kickoff meeting are related also to ultra-high intensities envisaged at ELI.[5]

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[2] Among the participants were R. Sauerbrey, T. Tschentscher, C.H. Keitel, A. Hartin, A. Wipf.

[3] C. H. Keitel surveyed in his plenary talk the present strong-field physics.

[4] Talks by R. Alkofer, C. Kohlfürst, G. Gregori, D. Blaschke, A. DiPiazza, T. Heinzl, A. Ipp, F. Karbstein, C. Rizzo, H.P. Schlenvoigt, C. Müller, R. Schüzhold, A. Takabe, H. Reiss in the order of the schedule.

[5] Cf. ELI documents "QED effects at ELI", A. DiPiazza et al., October 10, 2008; "Report on the ELI grand challenges, (Eds.) G. Korn and P. Antici, December 2009.

3.1 Probing the quantum vacuum by XFEL photons: birefringence, reflectivity and light-by-light scattering

In quantum field theory, the vacuum is the state with minimum energy determined by all possible interactions among virtual particles and fields. These vacuum properties get modified by an external field - one may say the vacuum becomes polarized and behaves as a medium (cf. [2]). Thereby, the XFEL can probe the vacuum which is polarized by the PWL. In QED, the process is described by the probe-photon self-energy, i.e. its polarization tensor. As a consequence [8], among others, an originally linearly polarized beam counter propagating through a strongly focused laser field acquires a nonzero ellipticity $\propto \Delta\varphi^2$ due to the difference of optical path lengths, where [9]

$$\Delta\varphi = \omega_{XFEL}\Delta_{PWL}|n_+ - n_-| \tag{1}$$

(Δ_{PWL} is the linear dimension of the PWL focal spot traversed by the probe beam). The occurrence of two refraction indices

$$n_\pm = 1 + \frac{1}{2}\lambda_\pm Q^2 \tag{2}$$

(here, $Q^2 = \vec{E}^2 + \vec{B}^2 - 2(\vec{E}\times\vec{B})\cdot\vec{n} - (\vec{E}\cdot\vec{n})^2 - (\vec{B}\cdot\vec{n})^2$ and $\lambda\pm = \frac{\alpha^2}{45m^4}(22\pm 6)$; $\vec{E}$ and $\vec{B}$ are the electric and magnetic field components of the external e.m. field and $\vec{n}$ stands for the direction of the probe photon; α is the fine structure constant) is the basis of the birefringence effect. As pointed out in [5], a_0 determines the amount of the birefringence even not made explicitly in (1, 2). A handy combination of (1, 2) reads $\Delta\varphi^2 = 3.2\times 10^5\left(\frac{\Delta_{PWL}}{\mu\mathrm{m}}\epsilon^2\nu\right)^2$ with $\epsilon = \sqrt{4\pi\alpha\vec{E}^2}/m^2$ and $\nu = \omega/m$ for $\epsilon\nu \ll 1$. (Note that we use natural units with $\hbar = c = 1$.)

The search for optimum configurations has been initiated by R. Sauerbrey [9] and resulted in the insight that the probe beam should have a polarization being inclined by 45 degrees relative to the linear polarization of the laser beam. Advances in the channel cut polarizer developments [10] make such a challenging experiment feasible according to design studies of the HZDR group [11]. A sketch of the envisaged setup is exhibited in Fig. 1.[6]

To put the proposed experiment into the proper perspective let us mention that vacuum birefringence is a feature of light-by-light scattering which has been predicted in 1934/35 [12] but never observed due to its small cross section. In this respect the observation of birefringence probes the "scattering properties of the vacuum aka light-by-light scattering" and is sensitive to

[6] In a precursor experiment, one could investigate, e.g., the Faraday rotation or the Cotton-Mouton effect, see [2] for details.

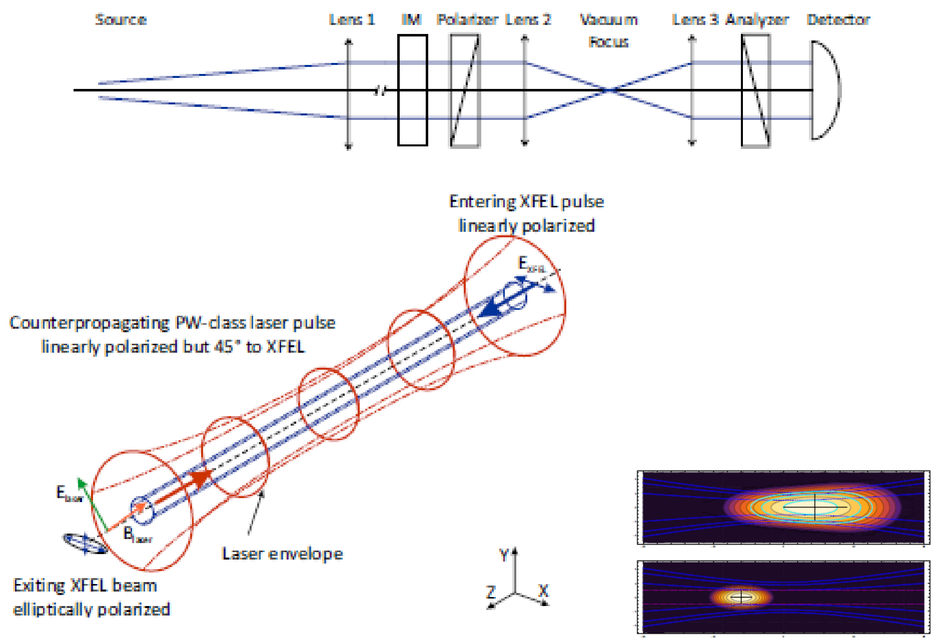


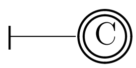
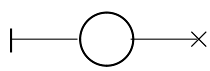
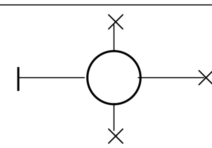
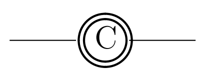
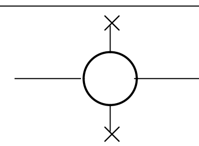
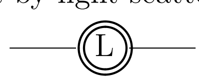
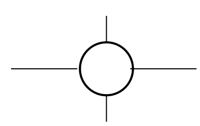
Figure 1: Schematic view of the setup planned for the first observation of the vacuum birefringence. Top: XFEL beam scheme, bottom left: XFEL and PWL beam arrangement, bottom right: intensity distributions of the PWL beam. From [11].

the forward scattering amplitude. Related effects include the photon polarization contribution to the Lamb shift which verifies the modification of the Coulomb law by virtual fluctuations (in lowest order being the Uehling correction). Delbrück scattering [13] probes, by propagating photons (light), the vacuum polarization provided by the Coulomb field of nuclei. It is the birefringence as a special aspect of the light-by-light scattering which probes by light the vacuum polarization provided by a free external field that is also propagating, i.e. is also light. Table 1 exhibits a survey on these different constellations. In Lamb shift, the vacuum is probed indirectly by the electron bound state depicted by "|" in the first row of Table 1. In contrast, in Delbrück scattering an incoming and outgoing photon probes directly the vacuum, as in the birefringence digram. To emphasize the differences of Delbrück and light-by-light scattering on a formal level[7] we mention that in

[7]The dependence of the dressed electron propagators as $S_F(\vec{x}, \vec{x}', t - t')$ for the former process and $S_F(x_+, x_+, x_{-,\perp} - x'_{-,\perp})$ for the latter one ($x_{\pm,\perp}$ are light front variables), i.e. due to the different symmetries one has one homogeneous variable vs. three homogeneous variables. These relations hold for a plane e.m. wave described, e.g., by the vector potential $\vec{A} = \frac{E_0}{\omega} g(\phi) \cos(\phi + \phi_0)\vec{e}$, $A^0 = 0$ in case of linear polarization. Here, E_0 is the maximum electric field in the wave of frequency ω, pulse shape $g(\phi)$ and carrier phase envelope ϕ_0; $\phi = k \cdot x$ is the invariant phase and $k \sim \omega(-1, \vec{1})$ the wave four-vector with $k \cdot k = 0$.

the former process the probe photons scatter off virtual photons from the Coulomb field (characterized by $F_{\mu\nu}F^{\mu\nu} > 0$ and $F_{\mu\nu}F^{*\mu\nu} = 0$) in a stationary and isotropic setting, while in the latter process real (i.e. propagating) photons (characterized by $F_{\mu\nu}F^{\mu\nu} = F_{\mu\nu}F^{*\mu\nu} = 0$) are scattered. In Delbrück scattering one has the background processes of Rayleigh scattering and nuclear Thomson scattering which exceed the Delbrück cross sections by orders of magnitude at low probe photon frequencies. Tat means in using laser photons to probe the vacuum polarization one uses a much cleaner environment with respect to competing background processes.

Table 1: Survey on loop diagrams. Thin lines - photons (emerging either from a Coulomb field at "×" or ending at an electron line "|" or being freely propagating ones), thick lines - electrons/propagators, double lines - dressed electron propagators (C: by a Coulomb field, L: by a laser field).

Furry picture diagrams	l.o. pert. expansion	further pert. diagrams
Lamb shift (vac. pol.) 		
Delbrück scattering 		
birefringence as a feature of light-by-light scattering 		

It should be stressed that the numerical value of the effect is sensitive to details of the theory. For instance, if other light particles beyond the Standard Model would exist, which couple to the e.m. field, they would contribute to the loop diagram and change the predicted effect. Milli-charges [14] represent such new particles. In addition, the actual prediction of the birefringence depends sensitively on the foundations of QED, such as Poincare invariance, space-time dimension, and vertex structure (current-field coupling). The estimates [9] of the expected birefringence effect are based on the Euler-Heisenberg effective theory, where electron loops are integrated out to arrive at a formulation with direct photon-photon interaction in a 4-vertex. There are other effective theory proposals, such as the Born-Infeld ansatz or more general formulations, which could be constrained further by the proposed

experiment. Only recently, a direct evaluation of the loop diagram with laser-dressed electron propagators has been accomplished [15]. This calculation evidences the sensible dependence on the structure of QED as a theory. To highlight the meaning of the mentioned effects one could denote them as exploration of the refractive/dispersive properties of the vacuum.[8] Above, it has been contrasted to vacuum polarization effects due to the Coulomb field. Using the phrases of T. Heinzl[9] in the questionnaires filled in during the kickoff meeting the exceptional meaning of the birefringence experiment can be characterized as follows:
- discipline specific challenge: precision test of the Standard Model in uncharted low-energy regime (optical + X-ray),
- research direction: high-precision and fine tuning of parameters required; - crucial parameters: X-ray polarization purity, beam shapes,
- XFEL and optical laser enabled innovation: probing optical laser focus by XFEL,
- outcome and potential impact: develop "vacuum optics" or optics without matter.

As stressed above, the experiment would be a flagship by the first observation of the "vacuum birefringence".
Quantum reflectivity [18] can be considered as some strong-field variant of the light-by-light scattering. It goes beyond the effective Euler-Heisenberg action by considering the above one-loop diagram for the probe-photon self energy with suitably dressed propagators. In essence, it is the reflection of a probe beam off the focal spot of either a laser beam or two counter propagating laser beams.

3.2 Towards quantum field theory in curved space-time: mimicking gravity effects in the search for signatures of the Unruh effect

In 1976, Unruh [19] considered the vacuum in the reference frame of an uniformly accelerated observer (acceleration a_U). His analysis culminated in the hypothesis that the observer "sees" a thermal bath of temperature $T_U = a_U/(2\pi)$, despite of the zero temperature of the vacuum in an inertial

[8] The absorptive part of the probe photon polarization tensor is related to pair production. Both the real and imaginary parts are linked by Kramers-Kronig type dispersion relations which are based on unitary of the scattering matrix. Vacuum birefringence is accordingly accompanied by a dichroism since the real and imaginary components $\pi_{1,3}$ of a decomposition of the polarization tensor enter the refraction and absorption characteristics as $n_\pm = (\mathrm{Re}\pi_3 \pm \mathrm{Im}\pi_1/\mathrm{Re})/\mathrm{Re}\omega_\pm^2|_{k^2\to 0}$ and $\kappa_\pm = (\mathrm{Im}\pi_3 \pm \mathrm{Re}\pi_1)/2\mathrm{Re}\omega_\pm^2|_{k^2\to 0}$, respectively, see [16]. Reference [17] proposes a test of unitarity relation via by phase contrast Fourier imaging but focuses also on birefringence.

[9] A. DiPiazza emphasizes the light-by-light diffraction effect, where real photons are scattered by real photons.

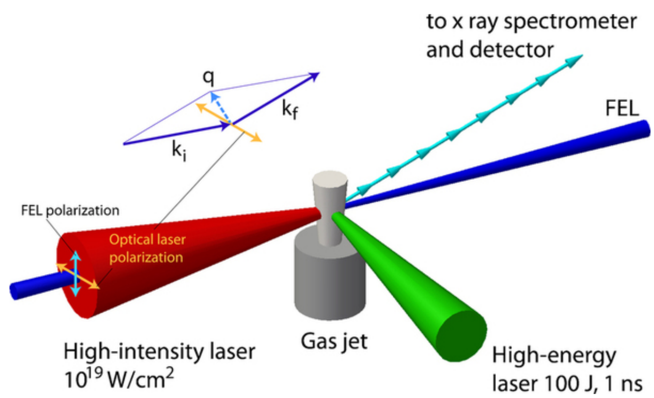


Figure 2: View of the setup planned for the first observation of signatures of the Unruh effect. From [22].

frame.[10] Since then a wealth of proposals (e.g. [20]) have been made to verify such an interesting effect which has a tight relation to the Hawking temperature of a Black Hole. The Unruh effect challenges the notion of particles in quantum field theory and is therefore of fundamental interest [21].

The proposal [22] (see Fig. 2) is aimed at a verification of a signature of the Unruh effect. In the laboratory, a broadening of the Thomson-scattered XFEL photon spectrum at accelerated electrons in a rapidly expanding laser-heated plasma [23] is envisaged. Reference [22] presents arguments for linking, by virtue of the equivalence principle, the large acceleration with a non-Minkowski space-time structure thus mimicking strong gravity effects. The scientific case and the presented feasibility estimates make such an experiment very compelling w.r.t. to a direct test of of quantum theory in curved space-time.

3.3 Search for new particles

Hitherto not detected particles are considered as candidates of Dark Matter. There is a large variety of proposals of hypothetical particles beyond the Standard Model. Among them are axions[11] or axion like particles or dark photons or milli-charges which have a coupling to e.m. fields. Light-shining-trough-a-wall experiments [25] aim at finding hints to these "new particles". The idea is that photons are converted into such new particles which, due to their very weak interaction, penetrate walls which are otherwise opaque for ordinary photons. Experiments need a conversion mechanism before and

[10] A Minkowski-space vacuum state for a free quantum field corresponds to a thermal state in the uniformly accelerated observer's frame.

[11] Axions have been introduced [24] to solve the strong CP problem that is related to the extraordinarily small neutron's electric dipole moment.

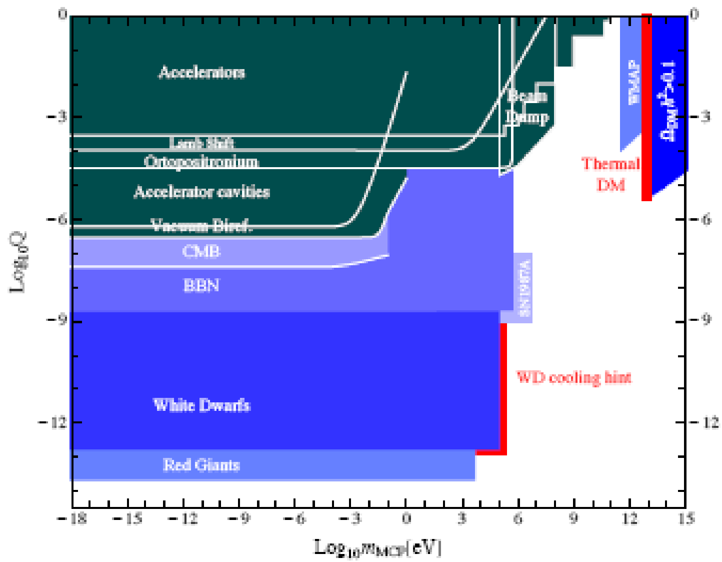


Figure 3: Exclusion plot (fractional charge Q vs. mass) for milli-charges. The colored regions are excluded by various constraints (cf. [26] for details). In the red marked regions, milli-charges would account for Dark Matter in the universe. From [26].

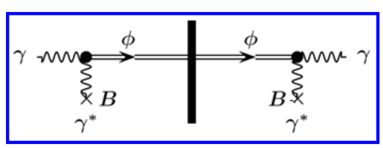


Figure 4: View of the setup planned for the search for new particles (ϕ) beyond the Standard Model in a light (γ)-shining-through-a-wall (heavy vertical bar) experiment. The (re)conversion is triggered either by a magnetic field (B) or a high-intensity laser (γ^*). From [27].

a recreation mechanism behind the wall. Previous experiments resulted in exclusion plots [26], e.g. for the coupling of the new hypothetical particles and their masses, since a positive signal transfer has not been detected. Fig. 3 exhibits an example for an exclusion plot for milli-charges.
The proposal presented by C. Rizzo [27] is based on the assumption of a light-light-particle coupling which converts the XFEL photons in the interaction with the PWL beam into a new particle and reconverts back, e.g. by a strong pulsed magnetic field or a synchronized second PWL pulse, the new particle into XFEL like photons, see Fig. 4. As the author emphasizes the use of XFEL photons as a primary beam would substantially enlarge the exclusion plots in case of a negative result since higher masses of the new particles would be probed.

3.4 Pair creation

A series of presentations at the HIBEF kickoff meeting addressed pair production. Since Schwinger's seminal prediction [28] of the change of an initially pure electric field E_0 into a configuration with e^+e^- pairs by a tunneling process, many ideas have been launched to look for a setup with present technologies to verify this fundamental process which is sometimes also termed "decay of the vacuum" or "breakdown of the vacuum". The verification is challenging since the pair creation rate goes as $\propto \exp\{-E_c/E_0\}$ where $E_c = m^2/\sqrt{4\pi\alpha}$ is the Sauter-Schwinger (critical) field strength. The large value of E_c makes the exponential, and thus the rate, exceedingly small for most laboratory situations. (Note the relation $a_0 = \frac{E_0}{E_c}\frac{m}{\omega}$. The structure of the exponential signals that a perturbative expansion does not exits.[12]
Proposals, such as the dynamically assisted Schwinger effect [31], try to overcome the small tunneling rate by "pumping" it with a multi-photon process. To be specific, a weak but high-frequency field (e.g., provided by XFEL) combined with a strong low-frequency field (e.g. provided in the anti-nodes of two counter propagating lineary plorarized PWL beams). The theoretical basis has been presented by R. Schützhold, R. Alkofer and C. Kohlfürst; the proposal to look for the transiently large quasi-pair excitations in the laser focal spot by a XFEL interference refractometer is made by D. Blaschke. Another variant of the non-perturbative Schwinger-like pair creation has been put forward by C. Müller, who also considered its relation to the non-linear Bethe-Heitler process in the multi-photon regime; the considerations are based to a large extent on the availability of a relativistic electron beam, where the Lorentz boosted e.m. field mimicks the strong field analog to a nucleus.
The relation of pair production as absorptive part of the light-by-light scattering amplitude has been emphasized already above.
If the output power of the XFEL would be upgraded, on the long term, to a level of $\mathcal{O}(100 \text{ GW})$ one could achieve multi X ray photon pair production: Focusing the radiation to the diffraction limit, pair production is estimated [32] to set in via the Schwinger mechanism in collisions with mildly relativistic nuclei, e.g. accelerated by the PWL [33]. In such a constellation one greatly benefits from the small XFEL wave length which allows, in principle, a very small focus leading to a significantly larger field strength.

3.5 Elementary photon-electron interactions

Nonlinear QED processes have been identified in multi-photon Compton scattering, $n\omega_L + e^- \to e^- + \omega'$, and the trident process, $n\omega_L + e^- \to e^- + e^+e^-$, in the famous experiment E-144 [34]. The experiment utilized the SLAC

[12] Note, however, that the non-linear Breit-Wheeler process (cf. [29]) has a similar dependence in the strong-field multi-photon region [30].

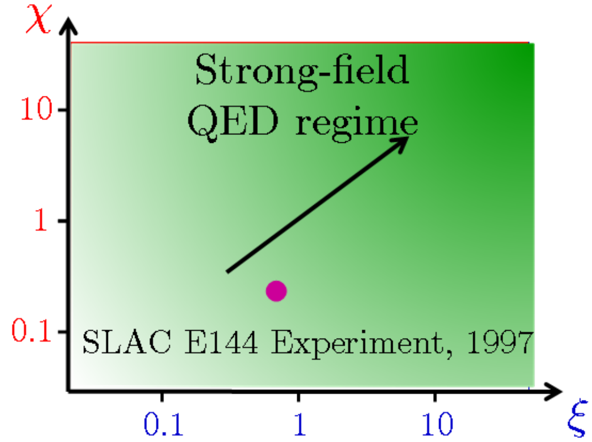


Figure 5: The parameter landscape χ vs. $\xi \equiv a_0$ with the location of the SLAC experiment E-144 [34]. From [39].

electron beam (46 GeV) in collisions with a Nd:glass laser beam at 527 nm ($a_0 = 0.4$). The involvement of $n = 4$ laser photons has been identified. Unfortunately, due to the weak laser beam, the experiment is just at the onset of nonlinear effects (see Fig. 5), and, due to low statistics, the precision is quite lausy. Therefore, better controlled precision experiments are urgently called for.[13]

A. Hartin proposed [35] to seek for the detection of Oleinik resonances due to Zel'dovich levels in 2-vertex multi-photon pair production or Compton scattering. The setup for the latter proposal (see Fig. 6) needs a common focal spot of a PWL beam and an electron beam which is probed by the XFEL beam. The corresponding QED process looks like the Compton diagram, however, with laser dressed electron wave functions and propagator. The investigations are expected to have impact on $\gamma - \gamma$ colliders and may allow for new avenues to cheaper accelerators.

Since more than 100 years, the equation of motion of a charged particle represents a challenge to electrodynamics and QED (cf. [1]). The question is about the proper form of the force K in the equation of motion $m\,\ddot{u} = K$, where K includes the external field, the charge's own field and the action of emitted photons. The latter effect goes under the name "radiation reaction". While on the first glance of academic interest (cf. [36] for a recent approach), it has stringent implications for the evolution of QED avalanches [37] seeded by a few electrons in ultra-strong fields: According to the simulations [38] the first steps of the evolution of the cascade is modified strikingly by including the radiation reaction force, see Fig. 7. A. DiPiazza made further proposals to identify the proper force term [1, 39] by emphasizing that, for $a_0 \gg 1$ and

[13] G. Dunne, DESY colloquium, July 9th, 2013.

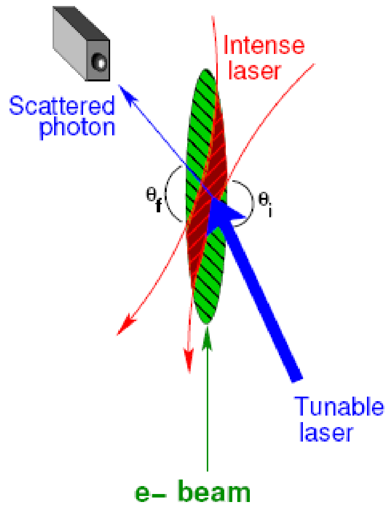


Figure 6: The experiment proposed in [35] to search for resonances in a 2-vertex process within a strong external field. From [35].

$\chi \sim 1$, multiple incoherent photon emission becomes important [40]; a region is identified in [41] where one of the photons is emitted outside the forward emission cone of single-photon Compton scattering. This extends previous studies of two-photon Compton scattering in long [42] and short [43] pulses.

4 The overall perspective

QED is a theory as part of the present Standard Model. The interpretation of cosmological and astrophysical observations, however, gives severe hints on its limitations: Dark Matter and Dark Energy [44] call for explanations which seem to be beyond the Standard Model. New fields and particles are candidates for such yet unexplained, but intensively searched for, forms of matter. While experiments of $g-2$ and atomic transitions enabled by the fine structure are at the frontier of precision in the weak-field regime (note that high-Z atoms probe also the strong-field regime, however, by different configurations implying different (quasi-)levels) of QED, the above considered experiments refer to the strong-field regime hitherto not yet explored by real photons and, consequently, offering a great scientific potential to verify fundamental effects predicted already a long time ago or to seek for new degrees of freedom. In relation with the much debated Unruh effect, even the foundations of the particle concept in quantum theory can be addressed by the unique opportunities offered by the XFEL-PWL constellation at HIBEF. The planned ELI pillars II (Debrecen) and III (Magiru) will provide, after the first beam delivery from XFEL, higher intensities than provided by the

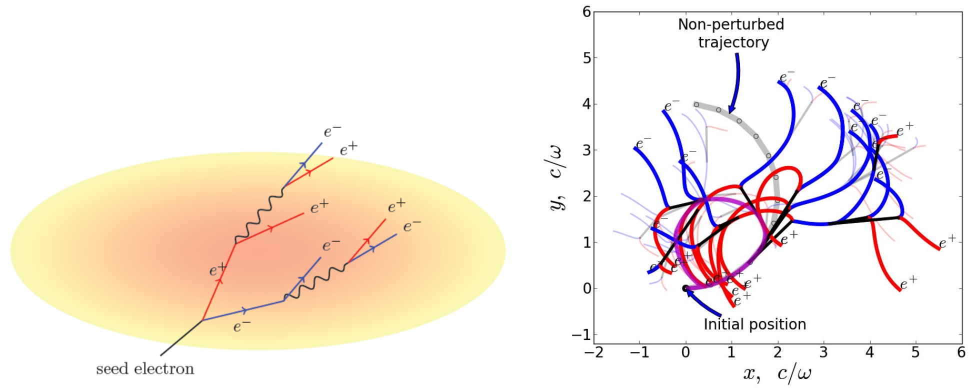


Figure 7: Initial stage of a seeded QED cascade. Left: the scheme, right: projection of trajectories with (colored) and without (gray) radiation reaction.[15] From [38].

PWL at HIBEF, but not in conjunction with such unprecedented properties as given by the XFEL. LCLS (Stanford) could be supplemented by a PWL system, but according to present plans and the overbooked beam time such an investment is not foreseen.

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