On The Detection Of Footprints From Strong Electron Acceleration In High-Intensity Laser Fields, Including The Unruh Effect

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Abstract. *The ultra-high fields of high-power short-pulse lasers are expected to contribute to understanding fundamental properties of the quantum vacuum and quantum theory in very strong fields. For example, the neutral QED vacuum breaks down at the Schwinger field strength of* $1.3 \cdot 10^{18}$ *V/m, where a virtual* e^+e^- *pair gains its rest mass energy over a Compton wavelength and materializes as a real pair. At such an ultra-high field strength, an electron experiences an acceleration of* $a_S = 2 \cdot 10^{28}$*g and hence fundamental phenomena such as the long predicted Unruh effect start to play a role. The Unruh effect implies that the accelerated electron experiences the vacuum as a thermal bath with the Unruh temperature. In its accelerated frame the electron scatters photons off the thermal bath, corresponding to the emission of an entangled pair of photons in the laboratory frame.*

In upcoming experiments with intense accelerating fields, we will encounter a set of opportunities to experimentally study the radiation from electrons under extreme fields. Even before the Unruh radiation detection, we should run into the copious Larmor radiation. The detection of Larmor radiation and its characterization themselves have never been experimentally carried out to the best of our knowledge, and thus this amounts to a first serious study of physics at extreme acceleration. For example, we can study radiation damping effects like the Landau-Lifshitz radiation. Furthermore, the experiment should be able to confirm or disprove whether the Larmor and Landau-Lifshitz radiation components may be enhanced by a collective (N^2) *radiation, if a tightly clumped cluster of electrons is accelerated. The technique of laser driven dense electron sheet formation by irradiating a thin DLC foil target should provide such a coherent electron cluster with a very high density. If and when such mildly relativistic electron sheets are realized, a counterpropagating second laser can interact with them coherently. Under these conditions enhanced Larmor and Unruh radiation signals may be observed.*

Detection of the Unruh photons (together with its competing radiation components) is envisaged via Compton polarimetry in a novel highly granular 2D-segmented position-sensitive germanium detector.

Keywords: high-intensity laser, Unruh effect, Larmor radiation, radiation damping, coherence, Compton polarimetry.

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INTRODUCTION

Understanding the structure of the quantum vacuum is one of the key challenges of contemporary fundamental physics. Our present deficit in understanding becomes evident when realizing the drastic failure of contemporary theoretical efforts to describe the observed energy density of the vacuum that amounts to about 4 GeV/m^3. Using quantum theory (QED) to estimate the energy density of the vacuum leads to the divergent integral of the ground-state energy density of the electromagnetic field, which could be treated by a cutoff at the Planck energy divided by the Planck volume. However, the hereby obtained Planck energy density is of order 10^{124} GeV/m^3 [1].

Moreover, quantum field theory in curved space-time predicts that the stress-energy tensor of a free quantum field in an adiabatic vacuum state in a slowly-expanding 4-dimensional universe should be of order L^{-4}, where L denotes the size or curvature radius of the universe. For our universe, 1/L would be of order $\sim 10^{-42}$ GeV ($\hbar=\omega=1$), corresponding to a vacuum energy density of $\sim 10^{-121}$ GeV/m^3 [2], again revealing a drastic discrepancy with the observational value. Consequently this discrepancy (also named the cosmological constant problem) was tagged as being the 'biggest embarrassment in theoretical physics' [1], raising severe doubts on our understanding of the basic concepts of quantum fields. The development of stable, ultra high intensity lasers has led to a renewed interest in strong field effects in quantum electrodynamics (QED). Examples include the search for long sought phenomena, such as the Schwinger pair production mechanism [3], which is a non-perturbative QED vacuum process.

Our experimental strategy exploiting the ultra-intense laser fields in a first step aims at a study of classical Larmor radiation, which to the best of our knowledge so far has never been observed for linearly accelerated charged particles. Moreover, experimental signatures for radiative back reactions ('radiation damping') will be targeted, aiming at an experimental proof or disproof of additional radiation damping terms added to the Lorentz force, like the ones introduced in the approach by Landau and Lifshitz [10].

Another quantum field theory prediction that may benefit from new experimental techniques is the Unruh effect [4]. Given the vacuum state experienced by inertial (Minkowski) observers, it has been shown [4] that uniformly accelerated (Rindler) observers with proper acceleration *a* will experience the fluctuations of the quantum vacuum as a thermal bath of particles ('warm gas') at the Unruh temperature (see Fig. 1),

$$kT_U = \hbar\, a/2\pi c \qquad (1)$$

So far no experimental identification of Unruh radiation as an analogy (via the Equivalence Principle) to Hawking's radiation of a black hole exists.

Recently an intriguing assertion has been put forward, that these radiation components may be collectively excited [26], exhibiting a coherence length determined by the driving laser wavelength in the inner rest frame of the accelerated electrons. This conjecture relates to the parallel given by synchrotron radiation, where such collective radiation is known to occur. It would be of utmost significance if this assertion could be experimentally verified. Even disproving the occurrence of coherent radiation would provide important new information as to a different behavior compared to synchrotron radiation.

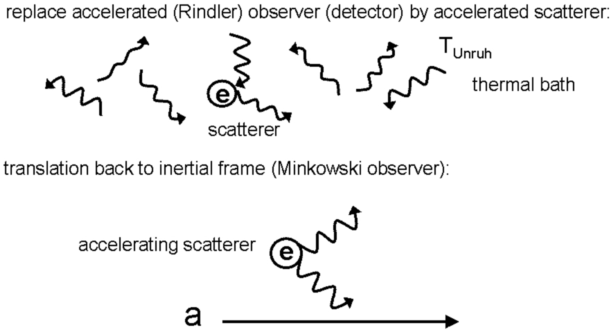

FIGURE 1. Schematical illustration of the creation of entangled photon pairs (Unruh photons) in the laboratory frame via non-inertial scattering of virtual photons off an accelerating scatterer.

Along with the only recent availability of ultra-thin nanometric target foils goes the expectation to be able to produce produce laser-accelerated extremely dense electron bunches near or even beyond solid density, which may act as coherent macro particles.

Combining the above assertions may result in a coherent enhancement of the experimental signature for Unruh radiation, representing a milestone in high field fundamental physics if indeed the underlying assertions as outlined above can be proven to be correct.

Signatures of the Unruh Effect

Replacing the accelerating observer (detector) by an accelerating scatterer (e.g. an accelerating electron) will result in non-inertial scattering processes with thermal (Rindler) photons. Translated back into the inertial laboratory frame the virtual photon will be converted to a real photon. As shown in [5], the translation back to the inertial frame of this process means that for each scattering event of (Rindler) thermal photons, as viewed in the co-accelerated frame, corresponds an emission of two (Minkowski) photons as viewed in the inertial/laboratory frame. As shown by Unruh and Wald [6], to every (Rindler) photon absorbed by an accelerated detector, as viewed in the co-accelerated frame, a corresponding (Minkowski) photon will be emitted in the inertial frame. This becomes obvious after realizing that the initial Minkowski vacuum is the ground state (in the inertial frame) and thus any alteration of the quantum state by such an accelerated detector can only imply an excitation, i.e., photon creation, for inertial observers. When replacing the detector by a scatterer, like an electron, it is reasonable that the scattering process, viewed in the co-moving frame as emission and subsequent absorption (i.e., *two* processes) of a (Rindler) photon, implies the emission of *two* (Minkowski) photons as viewed in the laboratory frame. Furthermore, this pair of photons will be entangled, and presenting properties that may be used to clearly distinguish it from the background of classical Larmor radiation also emitted in the laboratory frame due to the electron acceleration.

The Unruh effect is an analogy to the black-body Hawking radiation resulting from quantum fluctuations in the strong gravitational field of a black hole with mass M and surface gravity g [7], characterized by the Hawking temperature

$$kT_H = \hbar c^3 / 8\pi GM = \hbar g / 2\pi c \tag{2}$$

As simple as this equation for the thermal Hawking radiation may appear, one should note that it combines fundamental quantities from (yet) disparate fields of physics: gravity (G), quantum mechanics (ħ), thermodynamics (k) and relativity (c). While despite all theoretical efforts a quantized theory of gravity has not yet been formulated, Eq. 2 suggests an intimate underlying relation between these four physical regimes. Thus the Hawking equation (2) may act as a bridge, indicating the interplay between the various theoretical fields. The situation may be comparable to the early 1920s, when the theoretical description of the just discovered Compton effect was formulated within a semi-classical framework prior to the development of quantum mechanics. Via the Equivalence Principle the Unruh effect may allow an experimental glimpse into an otherwise experimentally inaccessible regime of fundamental physics.

Radiation Damping Effects

Classical Larmor radiation from accelerated electrons so far represents the dominant competing background to Unruh radiation. However, it also may allow experimental access to another long-standing fundamental problem in electrodynamics and QED: self-action effects of strongly accelerated charges. The well-known Lorentz force acting on an accelerated charge q reads as

$$mc\frac{du^i}{ds} = \frac{q}{c}F^{ik}u_k \tag{3}$$

with u and F^{ik} being the electron velocity and the electromagnetic field tensor, respectively. Since it does not take into account the back reaction of the energy loss via radiation (‘radiation damping’), it does not allow for a consistent description of the electron trajectory. This problem was extensively studied by many authors throughout the 20th century, starting with an extension of Eq. 3 by Lorentz and Abraham in 1904 [8], later extended by Dirac [9], resulting in the Lorentz-Abraham-Dirac (LAD) equation. Amongst the various model approaches the one given by Landau and Lifshitz already in 1962 [10] appears to be the most promising to cure the serious physical deficiencies of the LAD equation [11]. A second order differential equation was established that has been shown by Rohrlich [12] and Spohn [13] to lead to the physical submanifold of solutions for the case of asymptotically vanishing acceleration. A self-force term describing the radiation damping is added to the Lorentz force according to

$$mc\frac{du^i}{ds} = \frac{e}{c}F^{ik}u_k + F^i_{self} \tag{4}$$

with $$F^{i}_{\mathbf{self}} = \frac{2q^2}{3mc^3}\frac{\partial F^{ik}}{\partial x^l}u_k u^l - \frac{2q^4}{3m^2c^5}F^{il}F_{kl}u^k + \frac{2q^4}{3m^2c^5}\left(F_{kl}u^l\right)\left(F^{km}u_m\right)u^i \qquad (5)$$

While typically radiation damping effects can be treated as small perturbations to the Lorentz force, in the ultra-high field regime considered here together with novel laser acceleration techniques the self-force may become at least comparable to classical Larmor radiation, thus changing the characteristics of classical radiation competing with Unruh radiation significantly. Moreover, for the first time we may have an experimental access to validate the Landau-Lifshitz approach to radiation damping and to improve towards a self-consistent description of QED.

EXPERIMENTAL APPROACHES

The most promising experimental approach to study the Unruh effect in the laboratory was proposed in 1999 by Chen and Tajima [14]. They suggested using the interaction of a high-intensity laser field with an electron for testing quantum field theory in curved spacetime, especially to demonstrate the detection of Unruh radiation. With the enormous progress in the development of high-intensity, short-pulse lasers in recent years the experimental approach to Unruh radiation has reached a stage where its detection can be envisaged within the next years. While e.g. for the terrestrial acceleration *a=g* the resulting Unruh temperature $T_U = 4 \cdot 10^{-20}$ K = $3.3. 10^{-24}$ eV/k_B will stay far below any experimentally accessible range, novel short-pulse, high-intensity lasers will allow to push T_U into an experimentally accessible regime. Three experimental scenarios will be presented in this section, the first two describing the use of laser-accelerated incoherent electron beams either exposed to an oscillatory acceleration in the electric field of either an optical undulator or of an X-ray undulator, exploiting brilliant X-ray photon beams presently being developed via Compton-backscattering from a relativistic electron mirror. Moreover, the third scenario draws on the capabilities offered by using ultra-thin diamond-like carbon target foils (DLC). If the dense electron bunches off the DLC foil are to be accelerated coherently, interacting as macro particles as suggested in [26], it is suggested to enhance also Unruh radiation. We are situated to experimentally test this conjecture.

Generation of Unruh Radiation Using Incoherent Laser-Generated Electron Bunches

Several theoretical studies have been performed in non-linear QED resulting in quantitative predictions of yields for Unruh radiation as well as for the dominant background contribution, which is given by the classical radiation of accelerated electrons (Larmor radiation) [5,15,16]. In a first scenario with nearly constant proper electron acceleration, the probability for the emission of Unruh radiation scales with $P_{Unruh} \sim (E/E_S)^4$ (where E_S denotes the critical or Schwinger field strength $E_S = 1.3 \cdot 10^{18}$ V/m), thus requiring extremely strong electrical laser-generated fields near the critical field, while the short pulse leads to a broad Larmor background spectrum [5]. In contrast, an arrangement exploiting an oscillating acceleration provided by an undulator or a counter-propagating laser beam results in $P_{Unruh} \sim (E/E_S)^2$ and thus much relaxed experimental conditions. In this scenario relativistic electrons will be injected into the strong periodic field of an undulator or a laser. The resulting Lorentz-boost of the transversal field in the electron rest frame leads to an amplification of the electron acceleration. Whereas monoenergetic classical Larmor radiation with fixed polarization will be produced that exhibits a blind spot in acceleration direction, due to the Unruh effect photon pairs with opposite but otherwise arbitrary angular momentum direction will be created, obeying the resonance condition $k_1 + k_2 = \omega = 2\gamma\,\omega_0$ (k_1, k_2: wave numbers of Unruh photons, ω: boosted optical frequency in the electron instantaneous rest frame). Thus Larmor and Unruh radiation can be distinguished according to their different energy and angular characteristics.

In the first scenario electrons accelerated to relativistic energies (< GeV) [17-21] within distances of only a few millimeters together with the technique of coherent harmonic focusing [22] of an optical laser serving as undulator can be used to probe vacuum fluctuations by the creation of Unruh photon pairs in the energy region of a few hundred keV [23]. Using a TW (or PW) laser beam electrons can be accelerated in a gas-filled capillary to energies around 150 MeV (γ =300) with about 10^9 electrons/bunch. These electrons are then injected into a counter-propagating linear or circular polarized second laser (ps pulse length, 10^{18} W/cm^2, $\hbar\omega_{opt} \sim 2.5$ eV). In the instantaneous rest frame of the electrons this results for $E/E_S = 10^{-3}$ in a boosted optical frequency of 1.5 keV. As derived in Ref. [14], the emission probability for single Larmor photons from one electron after 100 laser cycles will result in $P_{Larmor} \sim 10^{-1}$, while the corresponding emission probability for Unruh photon pairs amounts to $P_{Unruh} = 4 \cdot 10^{-11}$.

A more favorable situation can be realized in the second scenario, where the optical undulator will be replaced by a brilliant X-ray beam, while the electron beam energy will be reduced to e.g. 1 MeV. Also this scenario allows to create ultra high electric fields, accelerating electrons such that Unruh photon energies measurable with modern γ-spectroscopic techniques will be produced. Such low-energy, yet monochromatic laser-accelerated electron beams can be realized using plasma density gradients in a gas jet decreasing in the laser propagation direction ('downramp'), thus allowing to control the wake phase velocity and trapping threshold in laser wakefield acceleration [24]. The resulting required primary photon energy $\hbar\omega_{0,2}$ amounts to about 20 keV. The low-energy electrons ($\gamma \sim 2$) interact with a brilliant X-ray beam produced from reflecting an optical laser beam off a relativistic dense electron mirror created by a driver laser focused onto a thin diamond-like carbon foil (DLC) with a thickness of typically only a few nm [25].

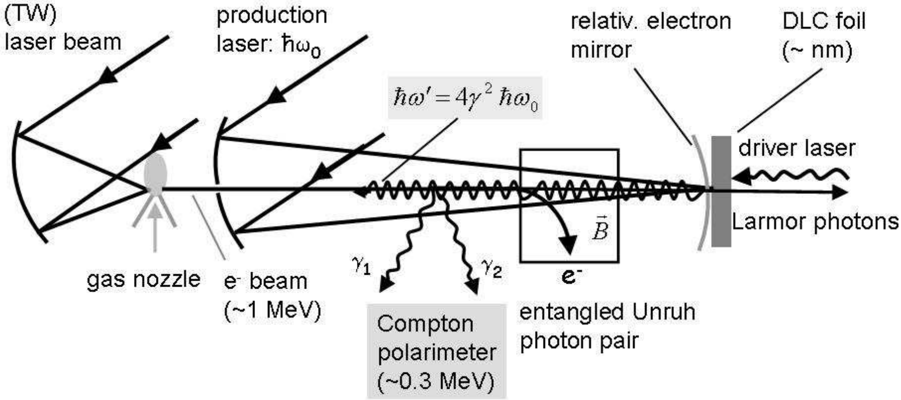

FIGURE 2. Schematical view of an experimental setup for the detection of Unruh radiation originating from laser-accelerated low-energy electrons interacting with a brilliant X-ray beam produced from reflecting an optical laser beam off a relativistic dense electron sheet (see text) used as undulator.

In the instantaneous rest frame of the electron this energy corresponds to $\hbar\omega_{int,2} = 2\gamma\,\hbar\omega_{0,2}$ = 80 keV. Thus the ratio between the photon frequencies in the rest frame increases by a factor of $\hbar\omega_{int,2}/\hbar\omega_{int,1}$= 53 when using the X-ray beam instead of optical laser photons. Now we have to remind that the probability for the emission of a (single) Larmor photon can be expressed as [15]

$$P_{Larmor} = \alpha_{QED}\,[qE/m\omega]^2 \cdot O(\omega T/2)\ , \qquad (3)$$

while the corresponding probability for the creation of a pair of Unruh photons is given by

$$P_{Unruh} = \alpha_{QED}^2\,[E/E_S]^2 \cdot O(\omega\,T/30) \qquad (4)$$

The ratio between the emission probability for Unruh photon pairs and single Larmor photons is determined by the ratio $(\omega/m)^2$. Therefore it is evident that by increasing the undulator frequency in the rest frame of the electron from 1.5 keV to 80 keV the probability for the emission of (single) Larmor photons will be reduced by a factor of about $2.8\cdot 10^3$, while the probability for the emission of Unruh photons remains unaffected. In addition the ratio between the electrical field strengths in the instantaneous rest frame of the electron in both scenarios differs by about a factor of 30 in favour of the X-ray undulator, therefore further increasing the gain factor by $(E^{int}_2/E^{int}_1)^2 \sim$ 850 to about $2.4\cdot 10^6$. Whereas in the previous scenario with an optical undulator the resulting ratio between the emission of Unruh and Larmor photons resulted in $P_{Unruh}/P_{Larmor} = 4\cdot 10^{-11}/10^{-1} = 4\cdot 10^{-10}$, this ratio now improves to about $9.6\cdot 10^{-4}$. Suitable angular and energy filters will allow to extract the Unruh radiation component from the still abundant classical Larmor background. Due to the small electron beam energy with γ =2 the resulting Lorentz boost and hence the forward focusing of the produced γ radiation will be significantly reduced, ending in an emission cone of about $1/\gamma \sim 15^\circ$ (compared to a much smaller angular segment with an opening of about 0.1° in case of $\gamma = 300$). Therefore the different emission characteristics between Larmor and Unruh radiation with the blind spot of Larmor radiation in acceleration direction can be exploited much more efficiently.

Testing Coherent Enhancement of Unruh Radiation

Exploiting the intriguing properties of ultra-thin foil targets may allow to drastically change the emission characteristics of photons created from the interaction of laser-accelerated electrons and strong laser fields, if the conjecture of coherently interacting electron macro particles, as discussed in more detail in Ref. [26], proves to be the case. In this scheme brilliant photon pulses can be generated extending from the keV- to multi- MeV photon energies. This will rely on the Thomson backscattering of photons with initial energy E_i on highly dense electron bunches driven out of ultra-thin foils of thicknesses of a few to tens of nm thickness by a driver laser (intensity I, wavelength λ, angular frequency ω_L) with a normalized vector amplitude $a_d^2 = I\,\lambda^2/1.38 \cdot 10^{18}$ Wcm^{-2} μm^2 (see Fig. 3) [25,27].

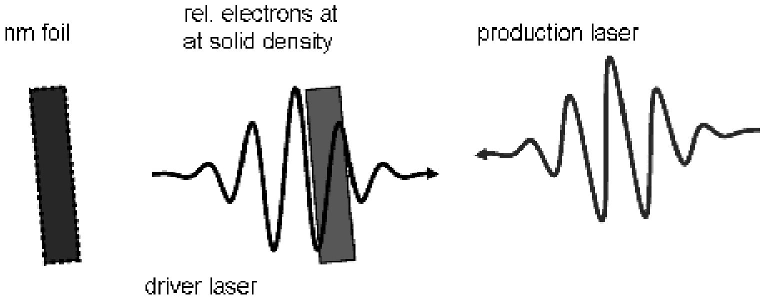

FIGURE 3. Schematical view of the principle of radiation pressure electron acceleration from an ultra-thin diamond-like carbon (DLC) foil. A strong driver laser pulse drives the electrons out of the thin foil, resulting in an overdense compression of the relativistic moving electron sheet. Compton-backscattering of a counter-propagating production laser may result in a coherent reflection of brilliant X-ray photons, if the corresponding claim discussed in [26] proves to be the case.

In order to produce such an highly dense relativistic electron mirror the breakout condition

$$a_d > n_e/n_c \cdot 2\pi d/\lambda_d \tag{5}$$

is necessary, where n_e is the electron density of the foil with thickness d and n_c is the critical density for the wavelength λ_d of the driver laser. It is interesting to note that whenever this condition is fulfilled, the thickness of the foil is much smaller than the collisionless skin depth which may allow us to treat all electrons inside the foil as coherently accelerated single particles in a plane wave. For this assumption to be justified we need furthermore to assume that the intensity of the driver laser does not vary too much over the transversal amplitude of an electron which in normalized units is a_d. The condition for the (normalized) focal spot radius of the driver laser $r_d > a_d$ ($r_d = r \cdot c/\omega_L$) then gives an upper limit for the reasonable driver laser amplitude

$$a_d < (8P_d/P_R)^{1/4} \qquad (6)$$

where P_d is the power of the driver laser and P_R=8.71GW is the relativistic power unit. For P_d = 200 PW we find a_d = 100, which limits the electron energies within the relativistic electron mirror. When treated as single electrons in a plane wave, which due to condition (6) is eventually fulfilled, an electron gains an energy according to $\gamma=1+a_d^2/2$ every half cycle of the driver wave. The photon energy of the reflected radiation then reads

$$E_r \sim E_I a_d^4 \qquad (7)$$

and enables the production of up to E_r = 100 MeV photons for backscattering optical photons with a_d=100. In the inner rest frame the electron density will be smaller by a factor of $1/\gamma$ due to the Lorentz contraction in the laboratory frame. At the time of the electron breakout the density in both systems will still be identical. One could argue that the ‚snow-plough' effect of the driver laser pushing the electrons from the back might confine the electrons and prevent them in the inner frame from Coulomb exploding. However, in the inner frame of the electrons the wavelength of the driver laser will stretch continuously and thus it will push with decreasing strength from the back. On the other hand from the front side an undulator or the production laser can compress the electrons. An estimate of the electron density in the rest frame amounts to n_e/γ. If electrons prove to behave according to this estimate, the laser trapping in the inner rest frame conserves n_e during acceleration, leading up to up to about 100 fold solid density in the inner frame. Recently the electron breakout by radiation pressure acceleration was observed for the first time [27].

The experimental scenario outlined below will allow to test the conjecture discussed in [26] that in the inner frame many electrons of the relativistic mirror belong to one phase cell of the light, and therefore may be regarded as one mesoscopic quantum mechanical macro particle. If this picture can be proven to be realized under laser acceleration conditions, the scattered wave amplitudes, which can be calculated independently for the individual electrons then have to be summed with their correct phases, leading to the coherent cross section, where the intensity scales quadratically with the number of emitting electrons N_e. Only in the direction of the reflection coherent superposition of the emitted amplitudes for the individual electrons occurs and leads to the emitted radiation. Here we remind that the emission probability for Unruh photons scales with $\alpha_{QED}^2 = (e^2/\hbar c)^2$, while for the competing Larmor radiation only a linear dependence on α_{QED} is found. Therefore, in case of acceleration of an electron macro particle the Unruh photon emission probability P_{Unruh} from a single electron as well as for Larmor radiation may be coherently enhanced. However, one has to take into account that the effective coherence volume will be different for Larmor and Unruh radiation: since the production laser exhibits transverse coherence over the entire electron sheet, in the case of classical Larmor radiation all N_e electrons inside the electron sheet may contribute. However, in the quantum case of Unruh radiation originating from scattering off vacuum fluctuations where the transverse coherence is determined by the wave length λ_{int} of the photons in the electron rest frame, the corresponding number N of coherent electrons contributing within the area λ_{int}^2 can be considerably smaller than N_e [26]. Nevertheless, if indeed the picture of coherently interacting electron macro particles proves to be the case, a drastic enhancement of the ratio between the Unruh and Larmor emission probability by $P_{Unruh}/P_{Larmor} \sim N^4/N_e^2$ can be expected.

Moreover, in this scenario radiation it is discussed that damping components may become comparable or even dominant compared to classical Larmor radiation, as expressed by Eq. 8, where the ratio between the conventional Lorentz force F_{ext} to the self force F_{self} from the radiative back reaction can be estimated as

$$\frac{F_{self}}{F_{ext}} = 10^{-8}\, a \frac{\omega}{\omega_L} \cdot N_e \tag{8}$$

With a being the normalized laser amplitude, ω the laser frequency in the inner frame of the electron and ω_L the laser frequency in the laboratory frame. Obviously the contribution from radiation damping dominates once the electron bunch contains a coherent macro particle in excess of about 10^8 electrons. Whether this condition can be realized largely depends on the size of the coherence volume.

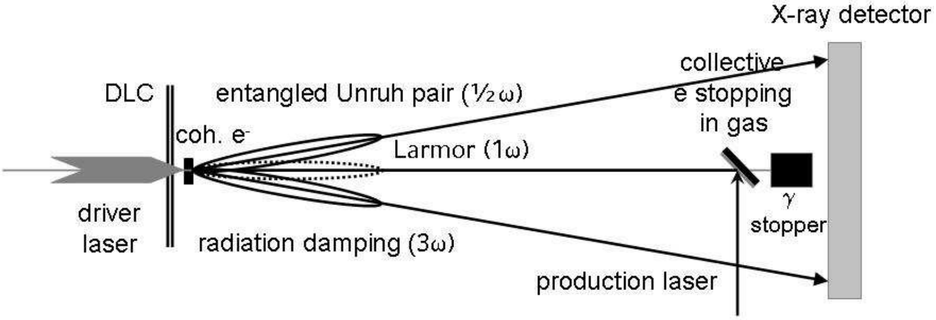

FIGURE 4. Schematics of an experimental setup for the detection of (entangled) Unruh photons and γ rays from radiation damping effects in the strong laser field, resulting from coherent reflection of an optical laser off a coherent electron bunch produced via radiation pressure acceleration in a thin DLC foil, thus aiming to test the scenario of generating coherent electron macro particles as outlined in [26].

Fig. 4 shows a schematics of an experimental scenario aiming at a verification of the generation of coherent electron bunches driven out of a thin DLC foil by an intense driver laser and interacting as macro particles as claimed in [26]. It is conceivable to achieve a value of $\gamma \sim 100$ for the accelerated electron bunches. A counterpropagating production laser ($\hbar\omega_{opt} \sim 2.5$ eV) acts as optical undulator for the electrons. Compared to the scenario depicted in Fig.2 electron acceleration is now required only to generate the electron bunch potentially containing coherently interacting macroparticles, replacing the previously individual electrons subject to strong acceleration in order to generate Unruh radiation. In the inner rest frame of the electrons the undulator energy is transformed to $\hbar\omega_{int} = 2\gamma \cdot \hbar\omega_{opt} = 0.5$ keV. Translated back to the laboratory frame, this relates to a reflected photon energy of 100 keV. In view of the similarity between parametric down-conversion and the emission of (entangled) Unruh photon pairs, this photon energy is converted into an entangled (Unruh-) photon pair with an average 50 keV each, obeying the Unruh resonance condition $k_1+k_2=\omega_{int}$. A photon energy of 50 keV is well-suited for detection in the Ge Compton polarimeter that will be described in the following section. When aiming at an optimized detection of Unruh photon pairs in an experiment testing the conjecture of coherent electron macro particles, adjusting the number of electrons contained in such a coherent bunch is essential. As long as N_e stays well below $\sim 10^8$, e.g. $N_e \sim 10^6$, from Eq. (8) it is obvious that classical Larmor radiation will still dominate the contribution from radiation damping effects. However, due to the coherent enhancement of P_{Unruh}/P_{Larmor} by N_e^2, the previous ratio of $\sim 10^{-11}$ will be increased to an about equal contribution of Larmor and Unruh photons, rendering an identification of the latter by far more realistic. Unlike in the conventional emission scenario, where classical (Larmor) radiation has a blind spot in acceleration direction, which can be used to identify Unruh photons being predominantly emitted into this direction, a dominant longitudinal acceleration from the radiation damping force would result in the emission of Unruh radiation into the maximum of classical radiation from the radiation damping force, thus advocating a suppression of this (in itself very interesting) radiation damping component by controlling N_e as discussed above. Moreover, a coherent reflection of the Unruh pair off the electron mirror requires their momenta to point perpendicular to the electron mirror surface in forward direction. Nevertheless the very different energetic emission characteristics for the various radiation components bears the potential of disentangling the individual contributions to the measured photon spectra in forward direction. As indicated in Fig. 4, the dense and short electron bunches are envisaged to be dumped via coherent deceleration in a gas cell [28], while the X-ray detector (i.e. the Compton polarimeter, see next section) placed under 0^o relative to the electron beam direction will be shielded from direct photon exposure by a massive γ stopper.

COMPTON POLARIMETRY

Experimentally the generation of entangled photon pairs can be identified via Compton polarimetry, where a measurement of the azimuthal Compton scattering angle will be sensitive to the polarization of the detected photons [30]. Fig. 5a) illustrates the kinematics of the Compton scattering process, i.e. the scattering of photons on free or quasi-free electrons. Here θ_c represents the Compton scattering angle, while $\hbar\omega$ and $\hbar\omega'$ correspond to the energy of the incident and scattered photon, respectively. The azimuthal scattering angle φ relative to the polarization plane of the incident photon, as determined via the Klein-Nishina formula, is the key observable for Compton polarimetry. As illustrated in Fig. 5a), two interaction points for scattering (X_1, Y_1) and absorption (X_2, Y_2) of the incoming γ ray ($E_\gamma = \hbar\omega$) define the azimuthal Compton scattering angle φ between the propagation direction of the scattered photon and the polarization vector of the incident photon. The differential Compton scattering cross section exhibits a characteristic angular dependency on φ with respect to the initial polarization vector $\vec{E}$. Due to the difference in polarization of the entangled pair of Unruh photons compared to the one of the classical radiation components, a measurement φ provides a sensitive tool to identify Unruh photons even amongst dominating background.

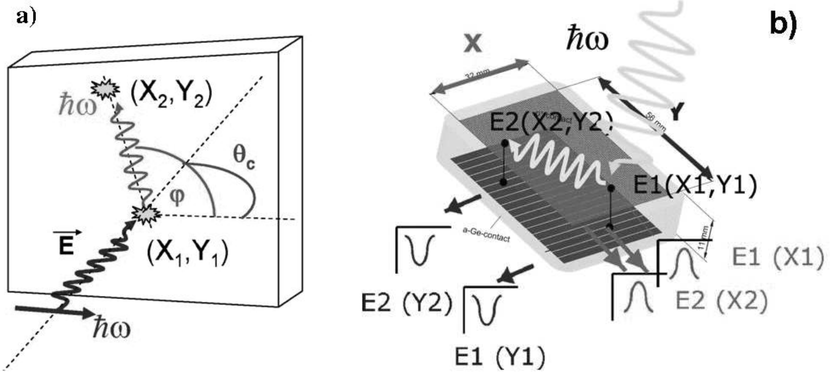

FIGURE 5. a) Kinematics of the Compton scattering process. In order to determine the azimuthal scattering angle φ relative to the polarization plane of the incoming photon the positions of two photon interaction points have to be determined: 1: scattering and 2: absorption. b) Schematics of the photon detection in a 2D-segmented γ detector, allowing for the determination of energies, x and y coordinates of the two interaction points of scattering and absorption within the same detector crystal.

Our experiments for the detection of radiation components from electrons strongly accelerated by laser fields (Unruh pairs, radiation damping photons) will be performed with a Compton polarimeter consisting of a planar, 20 mm thick, 2D-segmented germanium crystal, where both sides are segmented into 64 individual strips with 1 mm width each. The crystal is cooled to liquid nitrogen temperature and the 128 signals are read out by individual spectroscopy electronics chains. Comparable detectors have already proven high photon polarization sensitivity [30]. Fig. 6 shows a photograph of the detector system as available in Garching for the laser acceleration experiments.

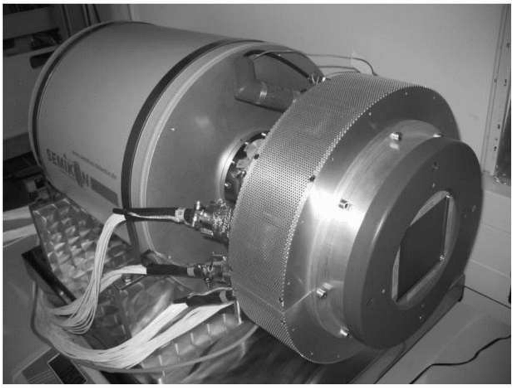

FIGURE 6. Compton polarimeter designed for the detection of entangled Unruh photon pairs with energies up to about 300 keV. The detector consists of a 20 mm thick, 2D segmented planar germanium crystal with 64 strips on either side (width 1 mm/strip), each read out by an individual chain of spectroscopy electronics.

CONCLUSION

In summary, we plan to detect and study the Larmor and radiation damping (Landau-Lifshitz) effects. Also the impact of their radiation by a tightly compressed electron bunch is studied, whether this will lead to enhanced radiation or not. If this proves to be positive, our detection sensitivity will increase by a large factor. If not, it also suggests an important implication indicating a different behavior compared to well-known synchrotron radiation, where coherent radiation has been observed.

Moreover, an experimental identification of entangled photon pairs as a signature of the Unruh effect is envisaged, exploiting the ultra-high field regime accessible with present and next-generation high-power, short-pulse lasers. A promising experimental scenario is given by using a brilliant 20 keV photon beam (created from Compton backscattering off a relativistic dense electron sheet) in conjunction with a low-energy laser-accelerated electron beam (γ~2). Using the X-ray beam as an undulator for the electrons will result in the creation of Unruh photon pairs well-separated in angle and energy from the main background contribution which is the classical Larmor radiation emitted by the linearly accelerated electrons. A drastically enhanced Unruh emission probability could be achieved, if coherent dense electron bunches generated via radiation pressure acceleration from ultra-thin carbon foils could be realized. If it can be experimentally verified that (parts of) the laser-accelerated electron bunches coherently act as macro-particles, this may significantly enhance the emission probability of Unruh photon pairs and grant first experimental access to radiation components from radiative back reactions on strongly accelerated charges. The identification of the Unruh radiation will be addressed by Compton polarimetry, using a highly granular 2D-segmented germanium spectrometer.

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REFERENCES

1. G. Fraser, *The New Physics for the Twenty-First Century*, Cambridge University Press, 2006.
2. S. Hollands and R.M. Wald, General Relativity and Gravitation **36** (2004) 2595; arXiv:gr-qc/0405082v1.
3. F. Sauter, Z. Phys. **69**, 742 (1931); ibid. **73**, 547 (1931); W. Heisenberg and H. Euler, Z. Phys. **98**, 714 (1936). V. Weisskopf, Kong. Dans. Vid. Selsk., Mat.-fys. Medd. **XIV**, 6 (1936); J. Schwinger, Phys. Rev. **82**, 664 (1951).
4. W.G. Unruh, Phys. Rev. D **14** (1976) 870.
5. R. Schützhold, G. Schaller, D. Habs, Phys. Rev. Lett. **97** (2006) 121302.
6. W.G. Unruh and R.M. Wald, Phys. Rev. D **29** (1984) 1047.
7. S.W. Hawking, Comm. Math. Phys. **43** (1975) 194.
8. M. Abraham, Ann. d. Phys. **14**, 236. 1904; H. A. Lorentz, Kon. Akad. v. Welenschappen te Amsterdam Mai 1902.
9. P.A.M. Dirac, Proc. Roy. Soc. London A **167** (1938) 148.
10. L.D. Landau and E.M. Lifshitz, *The Classical Theory of Fields,* second edition, §76 (Pergamon, London, 1962).
11. J.D. Jackson, *Classical Electrodynamics*, 2nd. ed., Wiley, New York 1975, p. 682.
12. F. Rohrlich, *Classical Charged Particles*, World Scientific, Singapore, 2007. F. Rohrlich, Phys. Rev. E 77 (2008) 046609.
13. H. Spohn, Europhys. Lett. **50** (2000) 287.
14. P. Chen and T. Tajima, Phys. Rev. Lett. **83** (1999) 256.
15. R. Schützhold, G. Schaller, D. Habs, Phys. Rev. Lett. 1**00** (2008) 091301.
16. R. Schützhold and C. Maia, Eur. Phys. Jour. D **55** (2009) 375.
17. S.P.D. Mangles et al., Nature **431** (2004) 535.
18. C.G.R. Geddes et al., Nature **431** (2004) 538.
19. J. Faure et al., Nature **431** (2004) 541.
20. W.P. Leemans et al., Nature Physics **2** (2006) 696.
21. S. Karsch et al., New Journal of Physics **9** (2007) 415.
22. S. Gordienko et al., Phys. Rev. Lett. **94** (2005) 103903.
23. P.G. Thirolf et al., Eur. Phys. Jour. D **55** (2009) 379.
24. C.G.R. Geddes et al., Phys. Rev. Lett. **100** (2008) 215004.
25. D. Habs et al., Appl. Phys. B **93** (2008) 349
26. D. Habs et al., this volume.
26. D. Habs et al., Eur. Phys. Jour. D **55** (2009) 279.
27. D. Kiefer et al., Eur. Phys. Jour. D (2009)
28. H.-C. Wu, T. Tajima, D. Habs, A.W. Chao, J. Meyer-ter-Vehn, arXiv:0909.1530v1 [physics.plasm-ph]
29. S. Tashenov, PhD thesis, Univ. Frankfurt, 2005, unpublished.
30. T. Stöhlker et al., Jour. of Phys. **58** (2007) 411.