Robust signatures of quantum radiation reaction and ultrashort gamma-ray pulses with an electron beam in a focused laser pulse

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Abstract

The interaction of a relativistic electron bunch with a counter-propagating tightly-focused laser beam is investigated for intensities when the dynamics is strongly affected by its own radiation. In dependence of the laser pulse duration we find signatures of quantum radiation reaction in the radiation spectra, which are characteristic for the focused laser beam and visible in the qualitative behaviour of both the angular spread and the spectral bandwidth of the radiation spectra. The signatures are robust with respect to the variation of the electron and laser beam parameters in a large range. They differ qualitatively from those in the classical radiation reaction regime and are measurable with presently available laser technology [1]. Additionally, we show for laser facilities under construction that gamma-ray bursts of few hundred attoseconds and dozens of megaelectronvolt photon energies may be detected in the near-backwards direction of the initial electron motion. Tight focussing of the laser beam and radiation reaction are demonstrated to be jointly responsible for such short gamma-ray bursts which are independent of both duration of electron bunch and laser pulse [2].

Robust signatures of quantum radiation reaction

We describe RR as emission of multiple photons during the electron motion in an ultrashort focused laser pulse[3] when the electron dynamics is accordingly modified following the photon emissions. In superstrong laser fields the invariant laser field parameter $\xi \gg 1$, the coherence length of the photon emission is much smaller than the laser wavelength and the photon emission probability is determined by the local electron trajectory, consequently, by the local quantum strong field parameter χ. The parameters $R \gtrsim 1$ and $\chi \lesssim 1$ are employed to ensure that pair production effects are negligible while quantum recoil effects remain important. The differential probability per unit phase interval is [4, 5]:

$$\frac{dW_{fi}}{d\eta d\tilde{\omega}} = \frac{\alpha\tilde{\chi}m^2[\int_{\tilde{\omega}_r}^{\infty} K_{5/3}(x)dx + \tilde{\omega}\tilde{\omega}_r\tilde{\chi}^2 K_{2/3}(\tilde{\omega}_r)]}{\sqrt{3}\pi(k_{0i}\cdot p_i)}, \qquad (1)$$

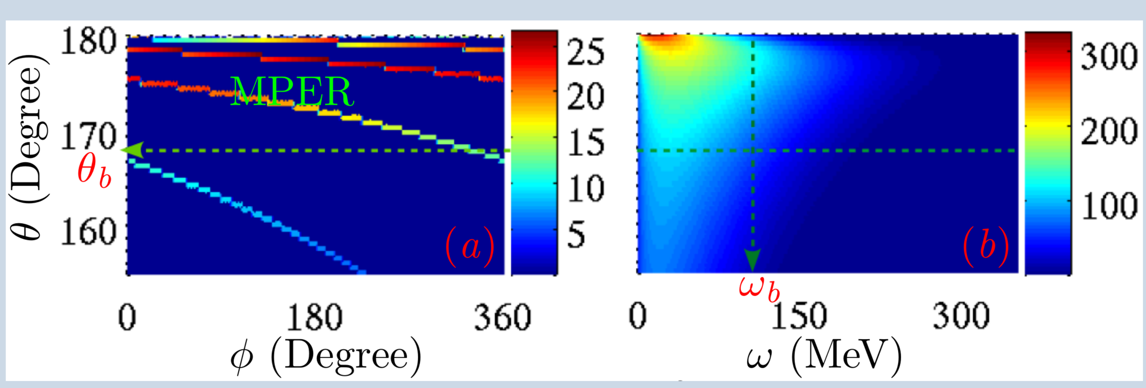

Fig. 1: The angle-resolved spectra of electron radiation in laser pulses of various durations: (a) dε/dΩ [GeV/sr], and (b) d$^2\varepsilon$/dωdΩ [1/sr] for $\tau_0 = 5T_0$. The laser wavelength is $\lambda_0 = 1\mu$m while $w_0 = 10\lambda_0$, ξ=230, and γ_0=1000. The emission angular spread $\Delta\theta \approx 180° - \theta_b$ with θ_b: $d\varepsilon/d\Omega|_{\theta=\theta_b} = (d\varepsilon/d\Omega|_{max})/2$, and the emission spectral bandwidth $\Delta\omega \approx \omega_b - 0$ with ω_b: $d^2\varepsilon/(d\omega d\Omega)|_{\theta=\theta_b,\omega=\omega_b} = (d^2\varepsilon/(d\omega d\Omega)|_{\theta=\theta_b,\max})/2$.

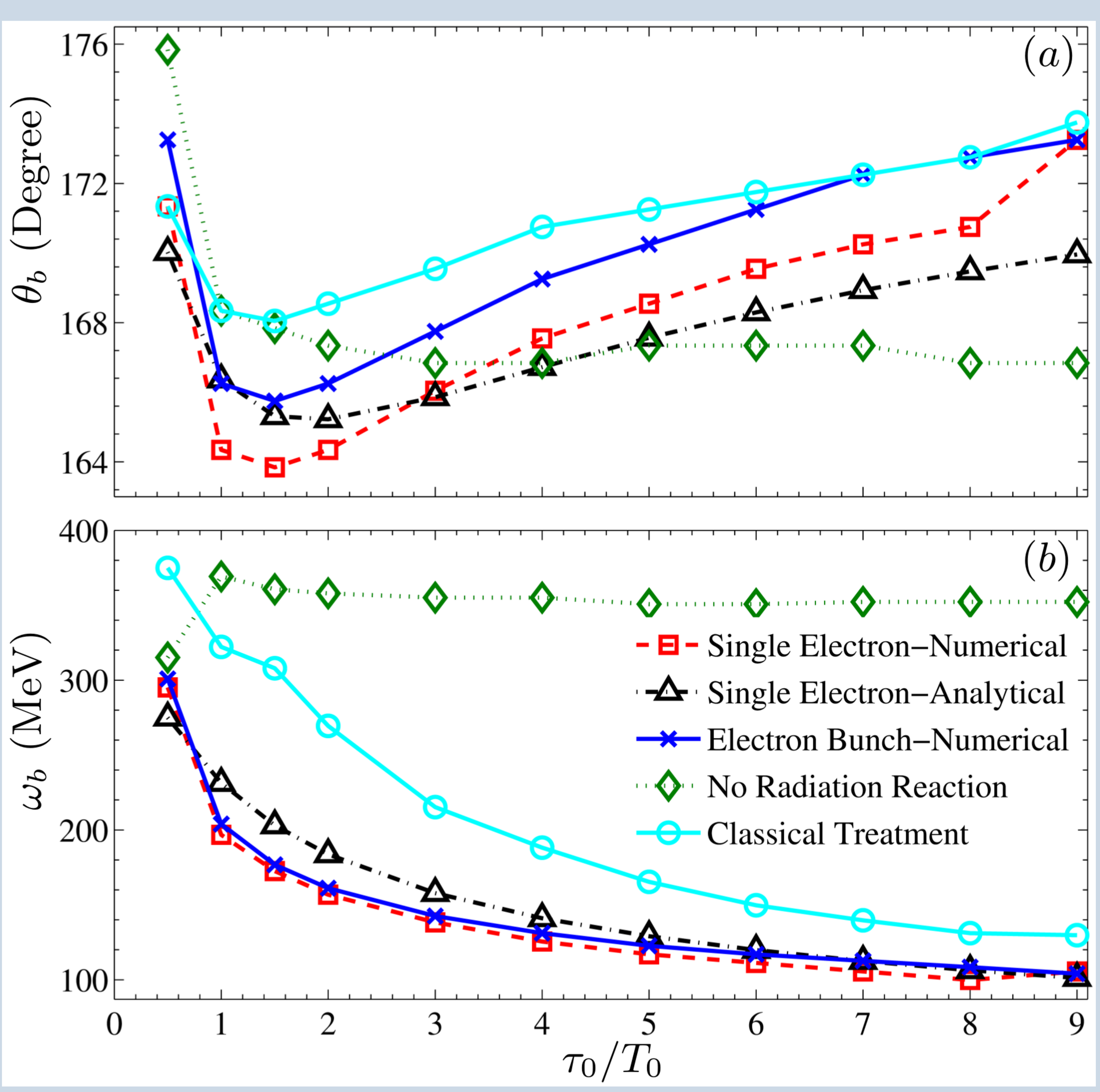

Fig. 2: The quantum RR signatures in the quantum radiation dominated regime (RDR). The boundary angle θ_b (a) and the boundary frequency ω_b (b) of the emitted photons are displayed in dependence on the laser pulse duration. The parameters are equal to those of Fig. 1.

where $\eta = \omega_0 t - k_0 z$, $\tilde{\omega} = k_{0i}\cdot k_i/(\tilde{\chi}\, k_{0i}\cdot p_i)$ is the normalized emitted photon energy, $\tilde{\chi} = 3\chi/2$, k_{0i}, k_i and p_i are the four-vectors of the driving laser photon, the emitted photon and the electron, respectively, and $\tilde{\omega}_r = \tilde{\omega}/\rho_0$ with recoil parameter $\rho_0 = 1-\tilde{\chi}\tilde{\omega}$ (in the classical limit $\rho_0 \approx 1$). The characteristic energy of the emitted photon is determined from the relation $\tilde{\omega}_r \sim 1$ and yields the cut-off frequency $\omega_c \sim \chi\varepsilon/(2/3+\chi)$. The rate of the electron radiation loss is $\mathcal{I} = \int d\tilde{\omega}(k_{0i}\cdot k_i)dW_{fi}/(d\eta d\tilde{\omega})$. Implementing the radiation losses due to quantum RR into the electron classical dynamics leads to the following equation of motion [5]:

$$\frac{dp^{\alpha}}{d\tau} = \frac{e}{m}F^{\alpha\beta}p_{\beta} - \frac{\mathcal{I}}{m}p^{\alpha} + \tau_c\frac{\mathcal{I}}{\mathcal{I}_c}F^{\alpha\beta}F_{\beta\gamma}p^{\gamma}, \qquad (2)$$

where τ is the proper time, $\tau_c \equiv 2e^2/(3m)$ and $\mathcal{I}_c = 2\alpha\omega^2\xi^2$ is the classical radiation loss rate [1].

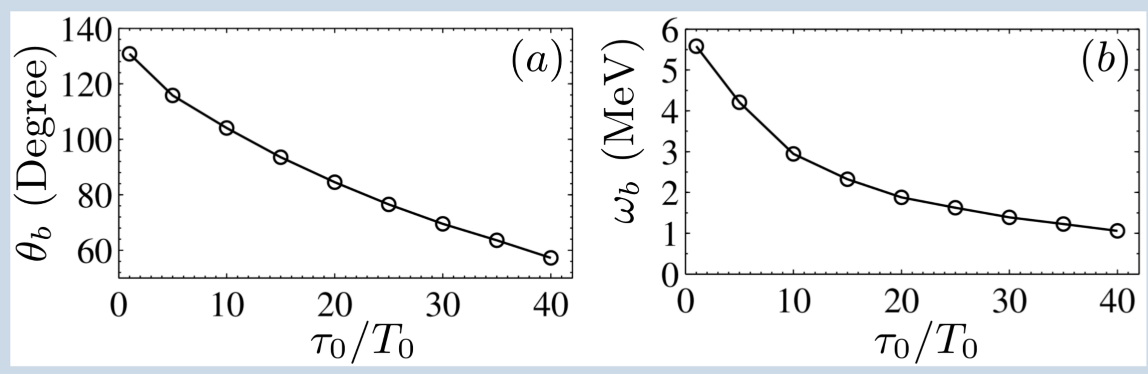

Fig. 3: The RR signatures in the classical radiation reaction (RR) regime. The variation of (a) the boundary angle θ_b and (b) the boundary frequency ω_b is displayed versus the laser pulse duration. $\xi = 100$, $\gamma = 100$, and the other parameters are equal to those of Fig. 1.

Attosecond gamma-ray pulses via nonlinear Compton scattering in the radiation dominated regime

We implement Monte-Carlo simulations of the electron radiation based on QED, while propagating the electrons between photon emissions according to classical equations of motion [6, 7, 8]. For the ultrashort gamma-ray production the following laser and electron parameters are required: $R = \alpha\xi\chi \gtrsim 1$ and $\chi \approx 10^{-6}\gamma\xi \lesssim 1$ for realizing quantum RDR, and $\gamma \sim \xi/2$ to allow for electron reflection, which finally requires $\xi \sim \gamma \sim 10^3$.

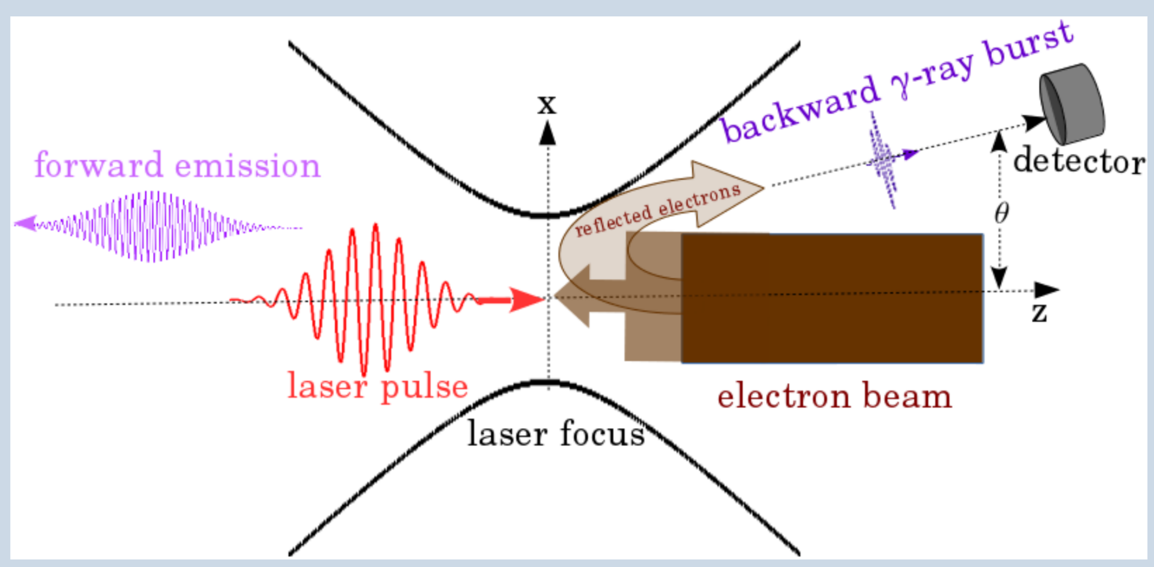

Fig. 4: Schematic scenario for the considered generation of ultrashort gamma-ray bursts which arise from a relativistic electron beam counterpropagating with a superstrong laser pulse. The front electrons of the electron beam loose sufficient energy due to radiation reaction to be reflected and to emit brief gamma-ray bursts when leaving the laser focal region.

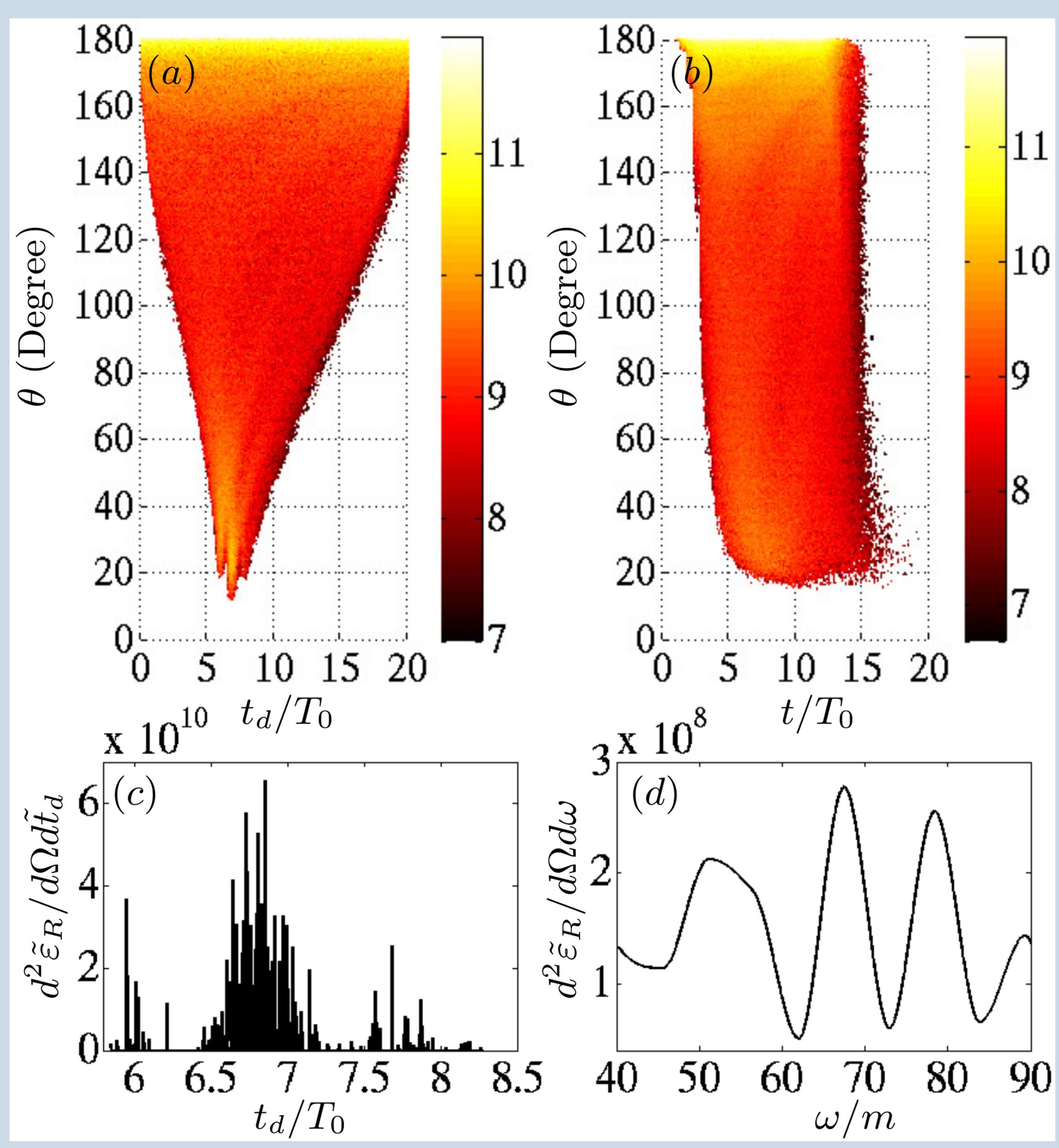

Fig. 5: The angle-resolved radiation intensity for photon energies above 1 MeV in a 4-cycle laser pulse with carrier-envelope phase $\phi_0 = 0$ and azimuthal angle of emission with respect to the laser propagation direction $\phi = 180°$: (a) in the detector time, $\mathrm{Log}_{10}(d^2\tilde{\varepsilon}_R/d\Omega d\tilde{t}_d)$ rad^{-2}, with $\tilde{\varepsilon}_R = \varepsilon_R/m$, $\tilde{t}_d = t_d/T_0$, radiation energy ε_R and emission solid angle Ω; (b) in the electron time, $\mathrm{Log}_{10}(d^2\tilde{\varepsilon}_R/d\Omega d\tilde{t})$, with $\tilde{t} = t/T_0$. (c) The gamma-ray pulse via $(d^2\tilde{\varepsilon}_R/d\Omega d\tilde{t}_d)\Delta\theta$ at $\theta = 20°$ and $\Delta\theta = 0.002$ rad. (d) The spectral distribution $d^2\tilde{\varepsilon}_R/d\Omega d\omega$ of the main pulse in (c). The laser parameters are $\lambda_0 = w_0 = 1$ μm, $I \approx 4.9\times10^{23}$ W/cm^2, $\gamma_0 \approx 392$. The electron bunch length here is $l_b = 10\lambda_0$, and the transverse size $w_b = w_0$. The energy as well as angular spread of the bunch is $\Delta\gamma/\gamma_0 = \Delta\theta = 10^{-3}$, the number of electrons in the bunch $N_e = 3\times10^8$, and the electron density $n_b \approx 3\times10^{19}$ cm^{-3}.

Between the photon emissions, the electron dynamics in the laser field is governed by classical equations of motion: $d\boldsymbol{p}/dt = -e(\boldsymbol{E} + \boldsymbol{v}\times\boldsymbol{B})$. Given the smallness of the emission angle $\sim 1/\gamma$ for an ultrarelativistic electron, the photon emission is assumed to be along the electron velocity. The photon emission induces the electron momentum change $\boldsymbol{p}_f \approx (1-\omega/cp)\boldsymbol{p}_i$, where $\boldsymbol{p}_{i,f}$ are the electron momentum before and after the emission, respectively, and ω is the emitted photon energy. During a small step of propagation $\Delta\eta$, the photon emission will take place if the condition $(dW/d\eta)\Delta\eta \geq N_r$ is fulfilled, where N_r is a uniformly distributed random number in $[0,1]$ (the value of $\Delta\eta$ is chosen small enough to keep the total number of photon emissions consistent). The photon energy ω is determined by the relation: $1/W\int_{\tilde{\omega}_{min}}^{\omega}(dW(\tilde{\omega})/d\tilde{\omega})d\tilde{\omega} = \tilde{N}_r$, where, $\tilde{N}_r$ is an another independent random number in $[0,1]$, and, $\tilde{\omega}_{min}$ is the minimal energy of the emitted photon, restricted by the laser photon energy. The radiation intensity is defined as the emission energy per unit detector time $t_d = t - \boldsymbol{n}\cdot\boldsymbol{r}(t)/c$, where $\boldsymbol{n}$ is the radiation direction and $\boldsymbol{r}$ the electron coordinate [2].

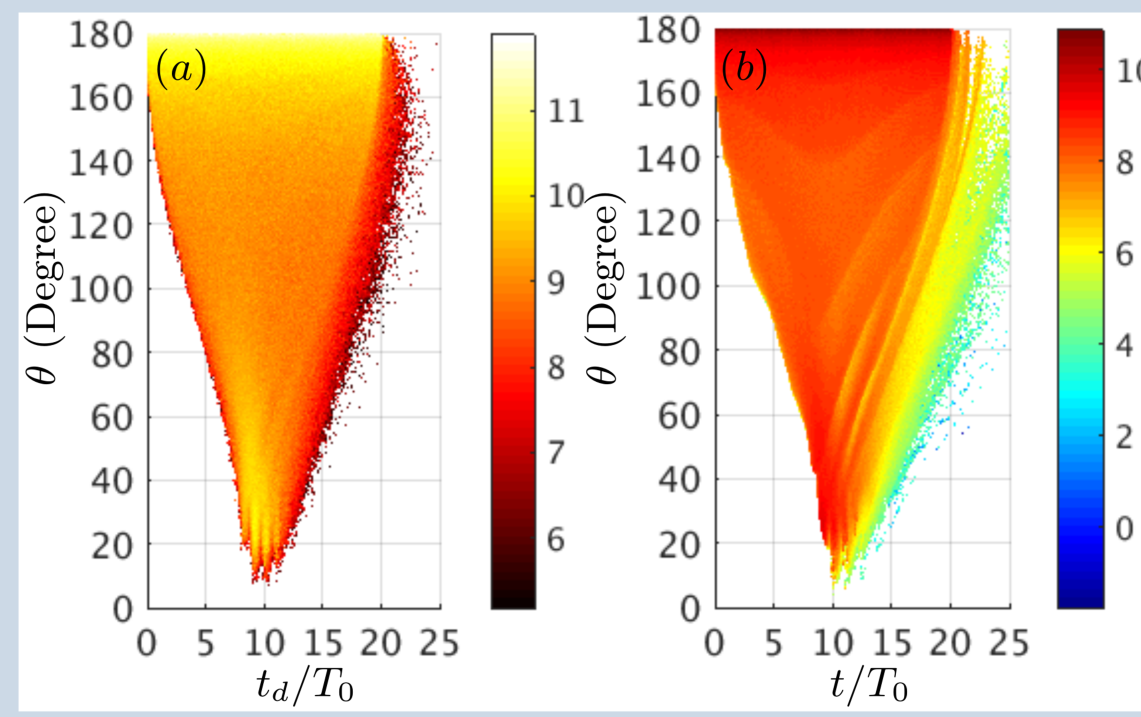

Fig. 6: The angle-resolved radiation intensity in a 6-cycle laser pulse in the detector time, $\mathrm{Log}_{10}(d^2\tilde{\varepsilon}_R/d\Omega d\tilde{t}_d)$ rad^{-2}: (a) including stochastic effects and (b) without stochastic effects using the method of Ref. [5] and $n_b \approx 10^{18}$ cm^{-3}. All emitted photons are included, and the other parameters are the same as in Fig. 5.

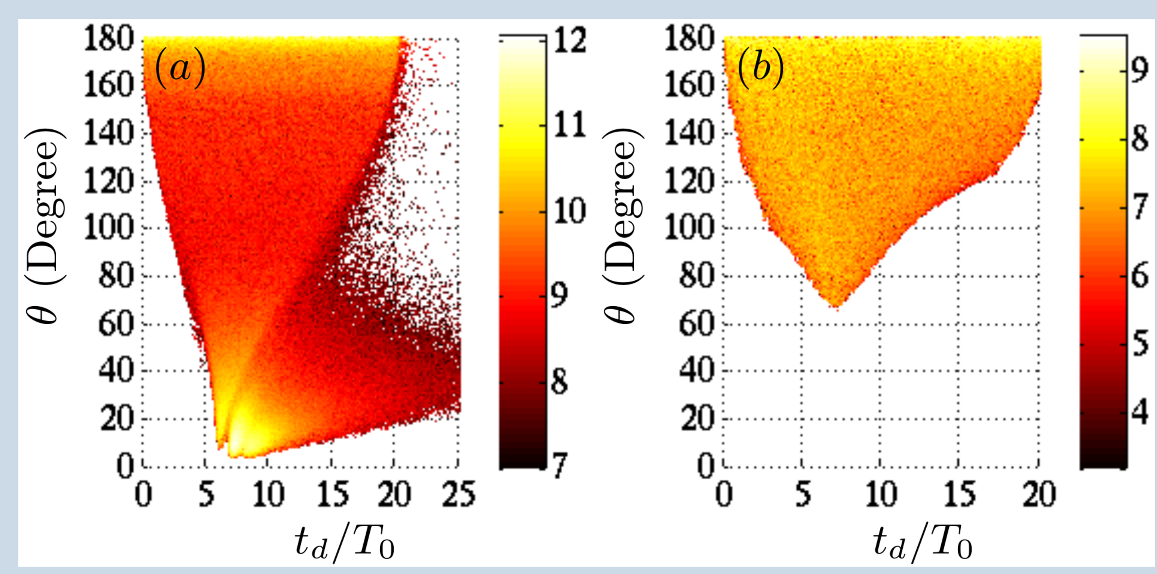

Fig. 7: The angle-resolved radiation intensity $\mathrm{Log}_{10}(d^2\tilde{\varepsilon}_R/d\Omega d\tilde{t}_d)$ rad^{-2} in a 4-cycle laser pulse: (a) in a plane wave laser field (only photons with energies above 1 MeV are included); (b) out of the radiation dominated regime with $\xi = 100$, $K_i = 20 \pm 0.02$ MeV (all emitted photons included). Other parameters are the same as in Fig. 5.

Conclusion

We have identified signatures of quantum RDR in dependence of both the angular spread and the spectral bandwidth of Compton radiation spectra on the laser pulse duration, which are distinct from those in the classical RR regime. Due to an interplay between laser beam focusing and quantum RR effects the angular spread of the main photon emission region has a prominent maximum at an intermediate pulse duration and decreases along the further increase of the pulse duration, and, the spectral bandwidth monotonously decreases with rising pulse duration. These signatures are robust and observable in a broad range of electron and laser beam parameters. Furthermore, we have shown that brilliant attosecond gamma-ray bursts can be produced by the combined effect of laser focusing and radiation reaction in nonlinear Compton scattering in the radiation dominated regime. A gamma-ray comb is formed when applying a long laser pulse, which carries signatures of stochastic effects in photon emissions.

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