Quantum radiation reaction in laser–electron-beam collisions

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Introduction

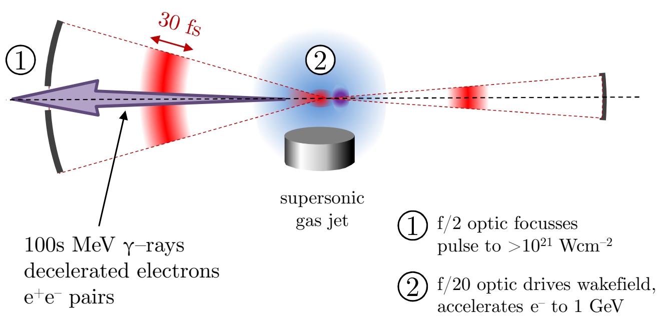


Figure 1: *An all-optical experiment that could demonstrate quantum radiation reaction: wakefield accelerated electrons decelerate in the focus of the short pulse, emitting gamma rays that pass through a hole in the f/2 optic.*

The ever-increasing intensity produced by high power, short pulse lasers has led to substantial interest into how radiation reaction and QED processes such as pair production will affect the plasma physics studied in future laser facilities.

It is likely that the interaction of a laser pulse of intensity $> 10^{23}\,\mathrm{Wcm}^{-2}$ with another laser pulse [1, 2] or with a solid density target [3, 4] will produce copious high energy gamma rays and electron-position pair plasmas.

Recently we have shown [5] how an experiment that could be accomplished in today's high intensity laser facilities, the collision of a GeV electron beam with a laser pulse of intensity $> 10^{21}\,\mathrm{Wcm}^{-2}$, could provide clear signatures of quantum radiation reaction. These are the increased yield of the highest energy gamma rays and the broadening in energy of the electron beam, caused by the stochastic nature of photon emission.

The importance of strong-field QED is determined by the parameter $\eta = |F_{\mu\nu} p^{\nu}|/mcE_{\mathrm{Sch}}$ [6], where $F_{\mu\nu}$ is the electromagnetic field tensor, p^{μ} (m) the electron four-momentum (mass) and E_{Sch} is the critical field of QED [7]. This field has equivalent intensity $I_{\mathrm{Sch}} = 2 \times 10^{29}\,\mathrm{Wcm}^{-2}$ and is unlikely to be realised in a laser facility in the forseeable future.

However, as η is the ratio of the electric field in the electron rest frame to E_{Sch}, it is possible to reach $\eta \sim 1$, and therefore the strong-field QED dominated regime, by pre-accelerating electrons to high energies. This has been achieved, and strong-field QED effects observed, in the collision of 100 GeV electrons with crystals at the CERN SPS [8], and in the collision of 50

GeV electrons with a $10^{18}\,\mathrm{Wcm}^{-2}$ laser pulse at the SLAC facility [9].

For an ultrarelativistic electron with Lorentz factor γ colliding antiparallel to a laser pulse of intensity I, $\eta \simeq 2\gamma\sqrt{I/I_{\mathrm{Sch}}}$. The f/2 parabolic optic of the Astra-Gemini laser may be capable of focussing a 30 fs, $\lambda = 1\,\mu$m laser pulse to a peak intensity $> 2\times 10^{21}\,\mathrm{Wcm}^{-2}$ (strength parameter $a_0 > 30$). Thus $\eta \sim \mathscr{O}(0.1)$ could be achieved with GeV electrons, and strong-field QED effects begin to become significant.

Theory

The electron motion in fields of this intensity will be dominated by radiation reaction. This can be modelled classically with the Lorentz-Abraham-Dirac force, which in the the Landau-Lifshitz prescription [10] adds to the electron equation of motion a term

$$\left.\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t}\right|_{\mathrm{rad}} \simeq -\frac{2\alpha_{\mathrm{f}}}{3}\eta^2 mc\hat{\mathbf{p}} \tag{1}$$

(where α_{f} is the fine-structure constant) which describes continuous loss of energy to radiation. However, when $\eta \sim 1$, this model fails because the typical energy lost in a single emission event, $0.44\eta\gamma mc^2$ [1], becomes comparable to the energy of the electron. Therefore the process of photon emission must instead be treated probabilistically.

In the framework of strong-field QED [11, 12, 13], the probability rate for an electron propagating in an intense EM field to emit a photon with normalised energy $\chi = (\hbar\omega/2mc^2)\sqrt{I/I_{\mathrm{Sch}}}$ is

$$\frac{\mathrm{d}^2\tau}{\mathrm{d}t\mathrm{d}\chi} = \frac{\sqrt{3}\alpha_{\mathrm{f}}}{2\pi\tau_{\mathrm{C}}}\frac{\eta}{\gamma}\frac{F(\eta,\chi)}{\chi}, \tag{2}$$

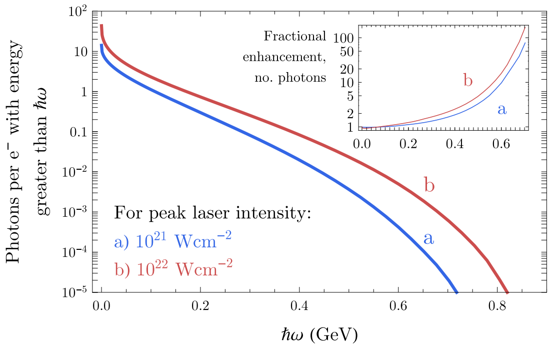
where τ is the optical depth against emission and the quantum synchrotron function

$$F(\eta,\chi) = \frac{4\chi}{3\eta^2}\left[\left(1-\frac{2\chi}{\eta}+\frac{1}{1-2\chi/\eta}\right)K_{2/3}(\delta) - \int_\delta^\infty K_{1/3}(t)\,\mathrm{d}t\right], \tag{3}$$

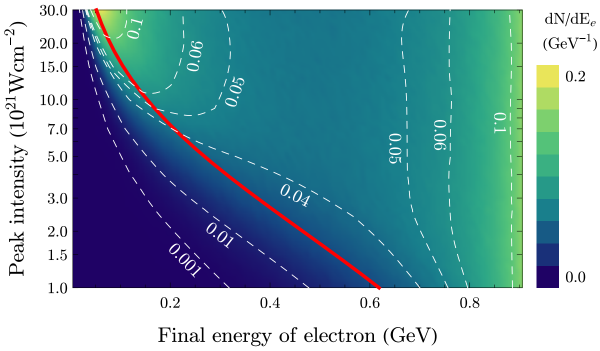
where $\delta(\eta,\chi) = (4\chi/3\eta^2)/(1-2\chi/\eta)$. It is non-zero only for $0<\chi<\eta/2$.

The fact that gamma ray emission is probabilistic will give rise to a phenomenon called 'straggling'. As it is possible for an electron to propagate a significant distance into the laser pulse without radiating, some electrons will reach the region of highest intensity at the pulse centre having lost much less energy than an equivalent classically radiating electron. The highest η that could be reached is then $\eta_{\max} = 2\gamma_0\sqrt{I_0/I_{\mathrm{Sch}}}$, where γ_0 is the electron's initial Lorentz factor and I_0 the peak intensity of the pulse. This will always be greater than the $\eta_{\max}$ that could be obtained classically. As the spectrum of emitted photons is controlled by $F(\eta,\chi)$, the high-energy tail of which increases non-linearly with η, straggling electrons emit more gamma rays with higher energy.

Figure 2: Simulation results.



(a) *The spectrum of photons emitted by a single GeV electron colliding with a laser pulse with given peak intensity. (inset) The factor by which straggling enhances the spectrum over that obtained semi-classically.*



(b) *The energy distribution of a GeV electron beam that forms a disk of radius 10 μm around the optical axis, after its collision with a laser pulse of given peak intensity. The red line is the lowest energy that can be reached by a classically radiating electron.*

Simulations

We have developed a Monte-Carlo code to simulate the collision of an energetic electron beam with an intense laser pulse. As $\gamma \gg a_0$, we neglect any transverse momentum gained from the laser fields and the space-charge field of the electron beam. The code includes both a fully stochastic model of radiation reaction and a continuous, semi-classical model.

In the former, the electron's optical depth τ is integrated along its trajectory according to (2): emission occurs when it reaches a pseudorandom 'final' optical depth $\tau_f \sim \exp(-\tau_f)$; the photon energy (and electron recoil) is obtained by sampling the distribution $F(\eta,\chi)/\chi$. In the latter, the electron loses energy continuously according to (1), modified to include a damping factor $g(\eta) \in (0,1)$. This is necessary because quantum corrections mean that the total power lost in synchrotron radiation is smaller than the equivalent classical power [11, 12].

The simulation parameters are: the laser pulse has wavelength 1 μm, linear polarisation and Gaussian temporal profile with a FWHM of 30fs; the electrons have initial gamma factor $\gamma_0 = 2000$, and propagate along the optical axis antiparallel to the laser pulse.

Modelling photon emission as stochastic leads to a dramatic increase in the yield of photons with $\hbar\omega \sim \gamma_0 mc^2$, because some electrons have straggled and consequently reached higher peak η. Fig. 2a shows this increase is greater than an order of magnitude for photons with $\hbar\omega > 500$ MeV. As there is no competing mechanism that could produce gamma rays of this energy, if detected, these photons would provide a clear signal that some electrons were incident on, and straggled through, the region of highest laser intensity.

Furthermore, as the electrons lose energy probabilistically, a monoenergetic beam will acquire a spread in energy as it propagates through the laser pulse, as can be seen in Fig. 2b. Detection of decelerated electrons would provide evidence of radiation reaction; the detection of electrons that have lost more energy than is possible classically would be evidence of specifically quantum radiation reaction.

Conclusion

It is now possible to probe the quantum radiation reaction dominated regime in a high-intensity laser facility. Using a laser wakefield to drive GeV electrons into a laser pulse of intensity $> 10^{21}\,\mathrm{Wcm}^{-2}$, we can obtain $\eta \sim 0.1$, at which point the stochastic nature of emission becomes manifest.

By attempting to detect either the enhanced yield of the highest energy gamma rays caused by straggling, or the consequently increased energy loss of the electron beam, we can obtain a good signal of strong-field QED effects at intensities in present day high intensity laser facilities.

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