Measuring radiation reaction in laser-electron beam collisions

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1 Introduction

Today's high-power laser facilities produce short pulses that reach peak intensities of 10^{22} Wcm^{-2} in tight focus [1] and wakefield-accelerate electrons to GeV energies in long focus [9, 8]. The radiation-reaction–dominated regime can be probed using the collision of such an electron beam with an intense laser pulse [4, 11] and detected in the substantial energy emitted as γ-rays (i.e. photons with energies in the MeV range) or the presence of a prominent depletion zone in the electron beam's post-collision energy spectrum [3]. These signatures of radiation reaction will be strong provided enough electrons penetrate the region of highest laser intensity. Our simulations of these interactions allow us to constrain the timing accuracy required to achieve this.

The importance of quantum radiation reaction may be quantified with the parameter

$$\eta \simeq \frac{\gamma\,|\mathbf{E}_\perp + \mathbf{v}\times\mathbf{B}|}{E_\text{Sch}} \tag{1.1}$$

where γ is the electron Lorentz factor, $\mathbf{v}$ its velocity, $\mathbf{B}$ the magnetic field and $\mathbf{E}_\perp$ the electric field component perpendicular to $\mathbf{v}$ [2]. η compares the magnitude of the electric field in the electron's rest frame to that of the critical field of QED $E_\text{Sch} = 1.3 \times 10^{16}$ Vcm^{-1}, which can produce electron-positron pairs directly from the vacuum [13].

In a laser-plasma interaction where the electrons typically have $\gamma \simeq a_0$, where $a_0 = [I(\lambda/\mu\text{m})^2/1.37 \times 10^{18}\ \text{Wcm}^{-2}]^{1/2}$ is the laser's strength parameter, I its intensity and λ its wavelength, we would expect that $\eta \simeq I\lambda/(5.65 \times 10^{23}\ \text{Wcm}^{-2}\mu\text{m})$ and intensities $> 10^{23}$ Wcm^{-2} would be necessary to observe strong-field QED effects [12, 5].

We can still reach the QED-dominated regime using today's laser facilities if the electrons are pre-accelerated to high energy before encountering the strong field region. This was accomplished in experiment E-144 at the SLAC facility [6], in which the collision of a 46.6 GeV electron beam and laser pulse of intensity 10^{18} Wcm^{-2} was observed to produce electron-positron pairs by photon–photon scattering.

Let us consider the collision of a GeV electron beam with a laser pulse of intensity 10^{22} Wcm^{-2}, as shown in fig. 1. The electron beam has parallel and perpendicular size 9 μm and 10 μm (full width at half maximum) and the energy distribution

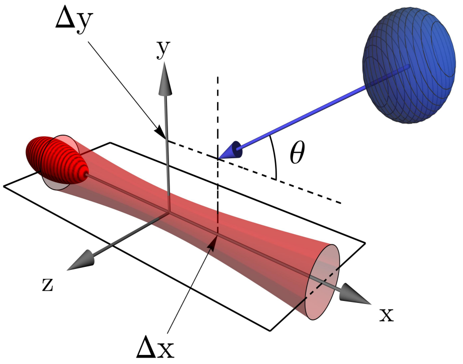

Fig. 1: Experimental configuration. A GeV electron beam (blue) collides with a laser pulse of intensity 10^{22} Wcm^{-2} (red). $(\Delta x, \Delta y)$ are the coordinates of the electron beam centre when the laser pulse is focused at the origin and θ the angle between the beams. (From Blackburn [3].)

$$f(\mathcal{E}) \propto (\mu + \sigma/3 - \mathcal{E})^{-3/2} \exp\left(-\frac{\sigma}{2(\mu + \sigma/3 - \mathcal{E})}\right) \tag{1.2}$$

for 100 MeV $\leqslant \mathcal{E} \leqslant \mu + \sigma/3$; it has a peak at $\mu =$ 1000 MeV and a width σ of 250 MeV. This has been chosen because wakefield-accelerated beam typically have large low-energy tails. The laser is a Gaussian focused beam with waist 2 μm and wavelength 0.8 μm, linearly polarised along the y axis. It moves towards positive x; the centre of the electron beam is located in, and its initial momentum is parallel to, the x-y plane.

The successful detection of radiation reaction depends on the degree of overlap between the beams. This is parameterised by $(\Delta x, \Delta y)$, the location of the electron beam centre when the laser pulse is focused at the origin, and the angle θ between the beams; we do not consider the effects of a displacement between the beams in the z-direction. We have performed simulations of this interaction for various Δx, Δy and θ using a single-particle Monte-Carlo code [3] to study the dependence of the γ-ray and electron energy spectra on the collision accuracy.

2 γ-ray production

Figure 2 shows the energy loss per electron of a GeV electron beam to gamma rays when colliding with a laser

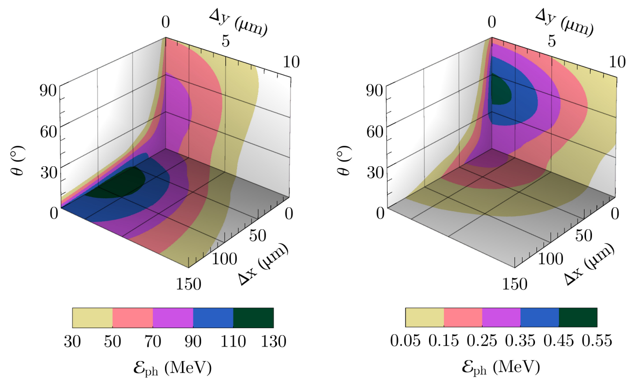

Fig. 2: The energy radiated by a GeV electron beam, per electron, to photons of all energies (left) and to photons with $\hbar\omega > 500$ MeV (right), when colliding with a Gaussian laser pulse of intensity 10^{22} Wcm^{-2} at an angle θ with parallel and perpendicular offsets Δx and Δy. (Adapted from Blackburn [3].)

pulse of intensity 10^{22} Wcm^{-2}. The total loss reaches a maximum of 120 MeV per electron for a head-on collision with a displacement $\Delta x = 80$ μm along the optical axis from the laser focus, but the largest loss to photons with energy > 500 MeV, 0.48 MeV per electron, occurs for a perfectly-timed collision with an angle between the beams of 50°.

There are three competing factors that determine the magnitude of the γ-ray yield: the geometric factor in η; each electron's length of interaction with the laser pulse; and the overlap between the electron beam and laser pulse. The first can be seen by evaluating (1.1) for an electromagnetic plane wave, with the result that $\eta = \gamma\,|E|\,(1 + \cos\theta)/E_{\text{Sch}}$, where θ is the angle between the electron momentum and the wavevector. As the radiated power $\mathcal{P} \propto \eta^2$ [10], the total gamma ray energy is maximised for a head-on collision.

However, for the highest energy photons, minimising the length of interaction is more important. The laser pulse is narrower than it is long, so electrons passing through it at an angle are more likely to *straggle* [14, 7], i.e. there is a higher probability of their reaching the pulse centre having lost little to no energy. As their η is boosted above that possible classically [4], the photons they emit are more energetic.

Finally, the degree of beam overlap explains why both yields shown in fig. 2 are so sensitive to the perpendicular displacement Δy; as it increases, fewer electrons encounter the high intensity region at the pulse centre. The total yield increases with Δx up to $\Delta x = 80$ μm because the laser pulse diverges as it propagates away from its focal plane and therefore more electrons encounter the pulse; however, as the intensity, and so η, decreases, the yield of high energy photons is reduced.

A head-on collision, the optimal configuration to produce gamma rays, can be achieved experimentally by

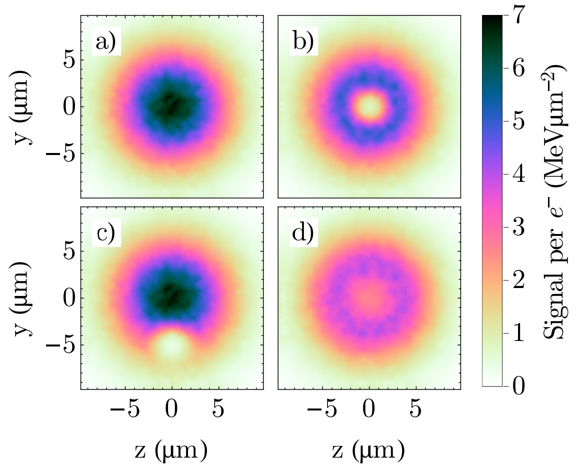

Fig. 3: The energy carried by the electron beam, per electron, per unit cross-sectional area a) prior to the collision and immediately after a collision at b) $\Delta x = \Delta y = 0$, c) $\Delta x = 0$, $\Delta y = 5$ μm and d) $\Delta x = 50$ μm, $\Delta y = 0$. (Adapted from Blackburn [3].)

using an optic with an aperture to focus the laser pulse to high intensity. Damage to the optical chain and back-reflection of the incident pulse can be avoided if that aperture is of sufficient size to permit the transmission of the wakefield-driving laser, the electron beam and resultant gamma rays.

3 Electron spectra

Radiation reaction could also be experimentally diagnosed by by comparing the energy spectra of wakefield-accelerated electron beams that have and have not collided with the target laser pulse and showing that the beam energy is reduced in the former case. However, even if $\Delta x = \Delta y = \theta = 0$, for which there is substantial loss of energy to γ-rays, the final energy spectrum is not sufficiently distinguished from (1.2) for this to be possible.

This is because the loss is dominated by those electrons that have collided with the intense part of the laser pulse; however, as the electron beam is broader than the laser pulse, most of it misses the high field region entirely. The broad energy spread of the beam is exacerbated not only by the range of intensities encountered by the electrons but by the stochasticity of emission as well: two electrons with the same initial conditions will not necessarily lose equal energies.

Were the electron beam well-characterised and reproducible, it would be possible to detect radiation reaction by comparing spectra from shots in the presence and absence of the target laser pulse. However, even high-quality wakefield-accelerated electron beams do not in general satisfy these requirements. An alternative method would exploit the fact that the laser pulse has a smaller diameter than the electron beam. Figure 3 shows the energy carried by the electron beam over its cross-sectional area for electrons that have collided with the laser pulse for various $(\Delta x, \Delta y, \theta)$. We can see by comparing a) and b) that the laser pulse causes significant depletion of the energy spectrum in a region of radius 2 μm around the optical axis. Resolving this areal energy spectrum could be accomplished by allowing the electron beam to diverge over a long distance as it propagates away from the collision point. A single shot would thereby allow the simultaneous measurement of the electron beam energy in the presence and absence of the target laser pulse and so the detection of radiation reaction.

4 Conclusion

The γ-ray yield and the energy loss of the electron beam are sensitive to both the maximal η reached by the electrons and the time it is sustained. However, the most significant factor will be the degree of overlap between the beams. Maximising this requires that the electron beam counterpropagate into the laser pulse, exploiting the slow angular divergence of the laser pulse, the geometric factor $(1 + \cos\theta)$ in η, and minimising the longitudinal accuracy necessary.

Our simulations show that the total γ-ray yield will be at least 80% of its maximum if

$$\left(\frac{\Delta x - 91\ \mu\mathrm{m}}{60\ \mu\mathrm{m}}\right)^2 + \left(\frac{\Delta y}{3.6\mu\mathrm{m}}\right)^2 \leqslant 1 \tag{4.1}$$

and the depletion zone in the electron spectrum will be significant (reduced by more than 3 MeVμm^{-2}) if

$$\frac{\Delta y}{4.6\ \mu\mathrm{m}} + \left(\frac{\Delta x}{61\ \mu\mathrm{m}}\right)^2 \leqslant 1. \tag{4.2}$$

Using the electron areal energy spectrum allows us to distinguish between electrons that have and have not collided with the target laser pulse, and so detect radiation reaction in an experiment that could be performed in one of today's high-intensity laser facilities.

References

[1] Bahk, S.-W., Rousseau, P., Planchon, T. A., Chvykov, V., Kalintchenko, G., Maksimchuk, A., Mourou, G. A., and Yanovsky, V., Opt. Lett. **29**, 2837 (2004).

[2] Bell, A. R. and Kirk, J. G., Phys. Rev. Lett. **101**, 200403 (2008).

[3] Blackburn, T. G., Plasma Phys. Control. Fusion **57**, 075012 (2015).

[4] Blackburn, T. G., Ridgers, C. P., Kirk, J. G., and Bell, A. R., Phys. Rev. Lett. **112**, 015001 (2014).

[5] Brady, C. S., Ridgers, C. P., Arber, T. D., Bell, A. R., and Kirk, J. G., Phys. Rev. Lett. **109**, 245006 (2012).

[6] Burke, D. L., Field, R. C., Horton-Smith, G., Spencer, J. E., Walz, D., Berridge, S. C., Bugg, W. M., Shmakov, K., Weidemann, A. W., Bula, C., McDonald, K. T., Prebys, E. J., Bamber, C., Boege, S. J., Koffas, T., Kotseroglou, T., Melissinos, A. C., Meyerhofer, D. D., Reis, D. A., and Ragg, W., Phys. Rev. Lett. **79**, 1626 (1997).

[7] Duclous, R., Kirk, J. G., and Bell, A. R., Plasma Phys. Control. Fusion **53**, 015009 (2011).

[8] Kim, H. T., Pae, K. H., Cha, H. J., Kim, I. J., Yu, T. J., Sung, J. H., Lee, S. K., Jeong, T. M., and Lee, J., Phys. Rev. Lett. **111**, 165002 (2013).

[9] Kneip, S., Nagel, S. R., Martins, S. F., Mangles, S. P. D., Bellei, C., Chekhlov, O., Clarke, R. J., Delerue, N., Divall, E. J., Doucas, G., Ertel, K., Fiuza, F., Fonseca, R., Foster, P., Hawkes, S. J., Hooker, C. J., Krushelnick, K., Mori, W. B., Palmer, C. A. J., Phuoc, K. T., Rajeev, P. P., Schreiber, J., Streeter, M. J. V., Urner, D., Vieira, J., Silva, L. O., and Najmudin, Z., Phys. Rev. Lett. **103**, 035002 (2009).

[10] Landau, L. D. and Lifshitz, E. M., *The Course of Theoretical Physics*, Vol. 2 (Butterworth-Heinemann, 1987).

[11] Neitz, N. and Di Piazza, A., Phys. Rev. Lett. **111**, 054802 (2013).

[12] Ridgers, C. P., Brady, C. S., Duclous, R., Kirk, J. G., Bennett, K., Arber, T. D., Robinson, A. P. L., and Bell, A. R., Phys. Rev. Lett. **108**, 165006 (2012).

[13] Schwinger, J., Phys. Rev. **82**, 664 (1951).

[14] Shen, C. S. and White, D., Phys. Rev. Lett. **28**, 455 (1972).