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Modelling gamma-ray photon emission and pair production in high-intensity laser–matter interactions

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ABSTRACT

In high-intensity ($>10^{21}$ W cm^{-2}) laser–matter interactions gamma-ray photon emission by the electrons can strongly affect the electron's dynamics and copious numbers of electron–positron pairs can be produced by the emitted photons. We show how these processes can be included in simulations by coupling a Monte Carlo algorithm describing the emission to a particle-in-cell code. The Monte Carlo algorithm includes quantum corrections to the photon emission, which we show must be included if the pair production rate is to be correctly determined. The accuracy, convergence and energy conservation properties of the Monte Carlo algorithm are analysed in simple test problems.

1. Introduction

High power lasers, operating at intensities $I > 10^{21}$ W cm^{-2}, create extremely strong electromagnetic fields ($E_L \gtrsim 10^{14}$ V m^{-1}). These fields can accelerate electrons sufficiently violently that they radiate a large fraction of their energy as gamma-rays within a single laser cycle. As a result the radiation reaction force becomes important in determining the electron trajectories [1]. In addition, quantum aspects of the radiation emission are important [2–5] and the emitted photons readily produce electron–positron pairs [6]. Gamma-ray photon and pair production can be investigated with today's petawatt-power lasers in specially arranged experiments. Furthermore, these emission processes will dominate the dynamics of plasmas generated by next generation 10 PW lasers [7–9]. In 10 PW laser–plasma interactions the QED emission processes and the plasma physics processes are strongly coupled. The resulting plasma is best defined as a 'QED-plasma', partially analogous to those thought to exist in extreme astrophysical environments such as the magnetospheres of pulsars and active black holes [10]. It is therefore highly desirable that gamma-ray photon emission and pair production be included in laser–plasma simulation codes. In this paper we will describe how these processes may be simulated using a Monte Carlo algorithm [4,5] and how this algorithm can be coupled to a particle-in-cell (PIC) code [11], allowing self-consistent simulations of QED-plasmas.

Several PIC codes have been modified to include a classical description of gamma-ray emission and the resulting radiation reaction [12]. The neglect of quantum effects limits the range of validity of such codes. The parameter which determines the importance of quantum effects in emission by an electron is $\eta = E_{RF}/E_s$ where E_{RF} is the electric field in the electron's

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rest frame and $E_s = 1.3 \times 10^{18}\ \mathrm{V\,m^{-1}}$ is the Schwinger field required to break down the vacuum into electron–positron pairs [13]. When $\eta \sim 1$: (i) classical theory predicts unphysical features, such as the emission of photons with more energy than the parent electron. Quantum modifications to the radiated spectrum are, therefore, essential [14,15]. (ii) A quantum description of photon emission is probabilistic and as a result the electron motion becomes stochastic [16]. (iii) The emitted photons are sufficiently energetic to readily produce electron–positron pairs [14]. These pairs go on to generate photons and thus further pairs, initiating a cascade of pair production [6].

The importance of quantum effects in current and next-generation laser–matter interactions can be estimated by assuming that $E_{RF} \sim \gamma E_L$, where E_L is the laser's electric field and γ is the Lorentz factor of the electrons. For current 1 PW lasers (intensity $I \sim 10^{21}\ \mathrm{W\,cm^{-2}}$) $E_L/E_s \sim 10^{-4}$. To reach $\eta > 0.1$, $\gamma > 1000$ is required. The laser pulse typically accelerates electrons to $\gamma \sim a$, where $a = eE_L\lambda_L/2\pi m_e c^2$ is the strength parameter of the laser wave (λ_L is the laser wavelength). For $I = 10^{21}\ \mathrm{W\,cm^{-2}}$ ($\lambda_L = 1\ \mu\mathrm{m}$), $a = 30$ and so in order to observe quantum effects the electrons must be accelerated to high energies externally. GeV electron beams, which can now be generated by laser–wakefield acceleration [17], are sufficient. The collision of such a beam with a 1 PW laser pulse could reach the $\eta > 0.1$ regime [18,19]. In fact this regime has recently been reached in similar experiments where an energetic electron beam, produced by a particle accelerator, interacts with strong crystalline fields [20].[2]

In the case where the electron beam is externally accelerated and then collided with a laser pulse, the plasma processes which cause the acceleration and the gamma-ray and pair emission during the collision are decoupled and may be considered separately. The same is true of recent laser–solid experiments where photon and pair production occur in the electric fields of the nuclei of high-Z materials far from the laser focus [23]. By contrast, in laser–solid interactions at intensities expected to be reached by next-generation 10 PW lasers ($>10^{23}\ \mathrm{W\,cm^{-2}}$, $\lambda_L = 1\ \mu\mathrm{m}$ [24]) $E_L/E_s \gtrsim 10^{-3}$ and $a \gtrsim 100$ and so the laser pulse itself can accelerate electrons to high enough energies to reach $\eta > 0.1$. In this case the emission and plasma processes both occur in the plasma generated at the laser focus. The rates of the QED emission processes for a given electron in the plasma depend on the local electromagnetic fields and the electron's energy, which are determined by the plasma physics processes. Conversely, the QED emission processes can alter the plasma currents and so affect the plasma physics. As a result the macroscopic plasma processes and the QED emission processes cannot be considered separately in the resulting QED-plasma.

In this paper we will describe a Monte Carlo algorithm for calculating the emission of gamma-ray photons and pairs in strong laser fields. In addition to being more widely applicable than a classical description of the emission, this quantum description of emission in terms of discrete particles is more suited to coupling to a Particle-in-Cell code. We will detail how this coupling can be achieved so as to self-consistently model the feedback between the plasma and emission processes; we will refer to the coupled code as 'QED-PIC' for brevity. QED-PIC codes based on this or a similar technique have recently been employed for simulations of both laser–plasma interactions [7–9] and pulsar magnetospheres [25].

2. The emission model

The emission model described here is detailed in Refs. [2] and [4]. For completeness, we will summarise the important details in this section. The electromagnetic field is split into high and low frequency components. The low frequency macroscopic fields (the 'laser fields') vary on scales similar to the laser wavelength and are coherent states that are unchanged in QED interactions. These fields behave classically [26] and are computed by solving Maxwell's equations including the plasma charges and currents smoothed on this length scale. Interactions between electrons, positrons and the high-frequency component of the electromagnetic field (gamma-rays) can be included using the method described by Baier and Katkov [27], in which particles (electrons, positrons and photons) move classically in between point-like QED interactions. The interaction probabilities are calculated using the strong-field or Furry representation [28], in which the charged particle basis states are 'dressed' by the laser fields. Feynman diagrams for the dominant first-order (in the fine-structure constant α_f) interactions included in the model are shown in Fig. 1 and represent: the emission of a gamma-ray photon by an electron accelerated by the laser fields (the equivalent process of photon emission by a positron is also included in the model) and the creation of an electron–positron pair by a gamma-ray photon interacting with the laser fields.

This approach rests on two approximations:

1. The macroscopic laser fields are treated as static during the QED interactions, i.e., 'instantaneous' and 'local' values of the emission rates are calculated. This approximation holds if the coherence length[3] associated with the interaction is small compared to λ_L. In the case of a monochromatic plane wave, the coherence length is λ_L/a [15], so the approximation is valid for $a \gg 1$.

2. The laser fields are much weaker than the Schwinger field. In this case we may make the approximation that the emission rates depend only on the Lorentz-invariant parameters: $\eta = (e\hbar/m_e^3c^4)|F_{\mu\nu}p^\nu| = E_{RF}/E_s$ and $\chi = (e\hbar^2/2m_e^3c^4)|F^{\mu\nu}k_\nu|$, p^μ (k^μ) is the electron's (photon's) 4-momentum; and are independent of the Lorentz invariants $\mathcal{F} = |E^2 - c^2B^2|/E_s^2$ and

[2] Other experiments have been performed where: a particle accelerator produced a beam of electrons with 46.6 GeV which subsequently collided with a laser pulse of $I = 10^{18}$–$10^{19}\ \mathrm{W\,cm^{-2}}$ [21]; laser wakefield acceleration produced electrons with broad energy spectra up to several hundred MeV which were collided with pulses with intensities $\sim 10^{18}\ \mathrm{W\,cm^{-2}}$ [22]. However due to the low laser intensity the radiation (and pair production in the former experiment) are in a substantially different regime to those considered here.

[3] In the classical picture the coherence length is the path length over which an electron (of energy $\gamma m_e c^2$) is deflected by $1/\gamma$.