Pair production and cascading in counterpropagating laser beams

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Introduction

Pair production has been reported in several experiments that used intense laser beams either as an accelerator (e.g. [3]) or as a target for electron beams [7]. Here we propose the use of laser beams both as an accelerator and as a target. This could be achieved using counterpropagating beams of intensity $10^{23} - 10^{24} \text{Wcm}^{-2}$ in an underdense plasma. Electrons accelerated this way radiate gamma rays, which can subsequently produce pairs via the multi-photon pair production process. As shown in a companion paper (Kirk, Bell, Arka, these proceedings, referred to as paper I in the following), these high energy photons reach energies of $775 I_{24}^{3/2} \lambda_{\mu m}^2 \text{MeV}$, where I_{24} is the single beam intensity in units of 10^{24}Wcm^{-2} and $\lambda_{\mu m}$ is the laser wavelength in microns. The produced pairs are expected to be accelerated inside the interacting pulses, and to lead to an electromagnetic cascade which could deplete much of the beam's energy.

Pulse models and electron acceleration

We have used realistic models of finite laser pulses to investigate the acceleration and radiation of electrons. The pulses are modeled choosing an envelope function

$$f_{\pm}(\phi) = \frac{1}{4} \left[1 \mp \tanh\left(\frac{\phi}{\Delta}\right) \right] \left[1 \pm \tanh\left(\frac{\phi \pm L}{\Delta}\right) \right]$$

by which we multiply a monochromatic plane wave of linear polarization. The phase is $\phi = z \mp ct$, L is the duration of the pulse, Δ adjusts the thickness of the pulse's edge and the upper(lower) sign refers to waves

Figure 1: *Shape of incoming and reflected pulse. The pulses are not plotted to scale.*

propagating in the $+z(-z)$ direction. We have chosen three different models: the beams have aligned polarizations, crossed polarizations, or aligned with the beam propagating in the $-z$ direction simulating a wave reflected by a solid target. This wave includes high harmonics [4]:

$$\mathbf{E} = \hat{\mathbf{x}} \frac{2}{\pi} \sqrt{\frac{\sqrt{3}}{2}} \sum_{n=0}^{n_{max}} \left(\frac{\sin[(2n+1)\phi_-]}{2n+1} - \frac{2\cos[(2n+1)]\phi_-}{\pi(2n+1)^2} \right)$$

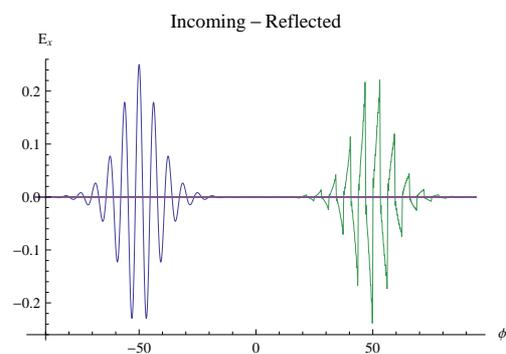The pulses are set to have a finite transverse size, and to occupy a cylinder with a radius of one wavelength.

We calculate the electron trajectory numerically using the classical equations of motion [1]

$$\frac{dp^i}{d\tau} = eF^{ij}p_j + g^i$$

where p^i is the four-momentum of the particle, F^{ij} the electromagnetic field tensor, τ the proper time and g^i the radiation reaction force given by the Landau-Lifshitz prescription [1]. The importance of quantum effects is determined by the Lorentz invariant parameter η, introduced in paper I. When $\eta > 0.1$ then quantum effects influence the electron motion, and pair production becomes important when $\eta \sim 1$. We do not take into account the discrete emission of photons, but we normalize the radiation emitted by the electron (and thus the radiation reaction force) by the reduction in the total power radiated in the quantum case in comparison to the classical case.

Pair creation and cascading

To calculate the pair creation rate by a single electron, the total optical depth τ_γ along a photon's path from emission until escaping the laser pulse is computed. The photon pair production rate is given by

$$\frac{dN_\pm}{dt} = \int_0^{\eta/2} d\chi \frac{dN}{d\chi dt}\left(1 - e^{-\tau_\gamma}\right)$$

where χ is a dimensionless photon frequency referred to in paper I, $E_{\text{cr}} = 1.3 \times 10^{18} \text{V m}^{-1}$ is the Schwinger field value and $\frac{dN}{d\chi dt}$ is the electron's instantaneous radiation spectrum. The trajectories of electrons in the beams are sensitive to the initial position of the particles. Electrons initially at rest are picked up by one of the pulses and accelerated along the pulse propagation direction. They emit strong radiation when they reach the pulse interaction region. However, in most cases they drift out of the cylindrical volume of the pulse before they reach this
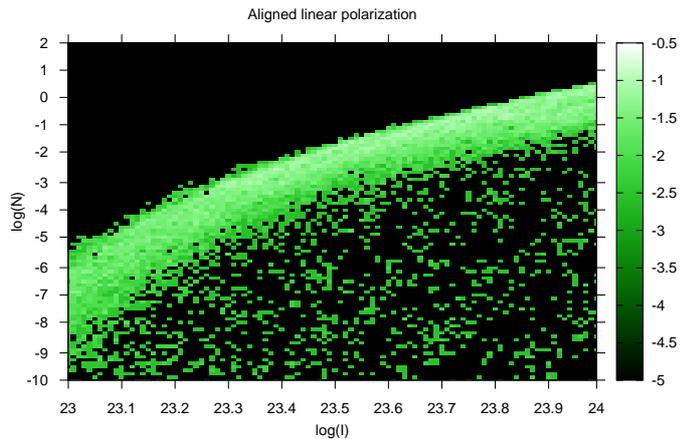

Figure 2: *Logarithm of pair creation probability per intensity bin in the case of aligned linear polarizations of the pulses.*

region. For this reason we have numerically computed trajectories with randomly chosen initial positions in the range $-8\lambda < z < 0$ and randomly chosen *x,y* on a disc of radius λ. The intensity of the beams is also randomly chosen in the interval $23 < \log I_{24} < 24$. We computed 10^5 trajectories for each beam model discussed above. For the details of the calculation, see [6].

The results can be seen in figures 2,3,4. Each figure corresponds to a different beam model. We have plotted the logarithm of the probability that a certain number of pairs will be created if an electron starts from rest with random initial position in a given logarithmic intensity interval. In the cases of the reflected pulse and aligned polarisation rougly 83% of the particles leave the laser volume without having triggered pair production, while in

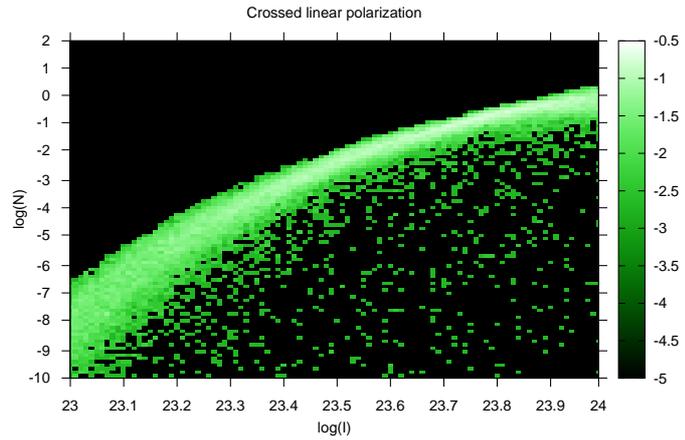Figure 3: *Logarithm of pair creation probability in the case of crossed linear polarizations of the pulses.*

the crossed polarisation case this percentage is close to 75%.

Pair cascades should begin to develop when each electron produces roughly one pair before it escapes from the beams. From figures 2,3 and 4 we see that only for the highest intensities is the probability of the creation of one pair non negligible. For example, in the aligned linear polarization case, the critical intensity for pair creation is seen to be $\log I_{24}^{\mathrm{cr}} \sim -0.14$. The three different beam configurations produce similar results.
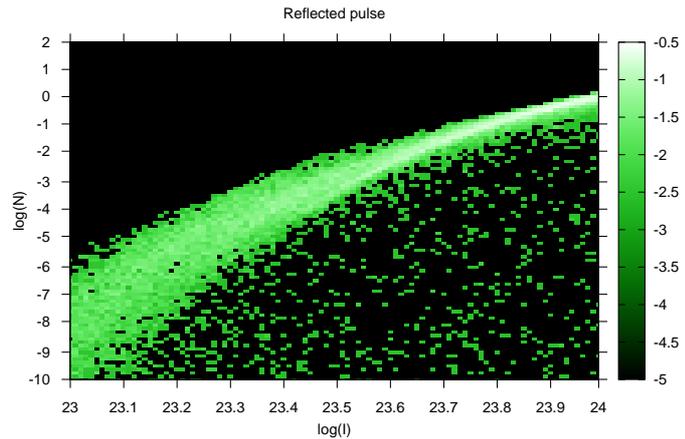

Figure 4: *Logarithm of pair creation probability per intensity bin in the case of the interaction with a reflected beam.*

The above calculations show that a significant percentage of the electrons is going to emit

radiation energetic enough to produce pairs on the beam photons if beams of intensity close to 10^{24}Wcm^{-2} are counterpropagating in an underdense plasma. Most of this radiation is emitted at the region where the pulses interact. Because the pairs are produced in this region, they get rapidly accelerated and thus can produce energetic radiation themselves. This should result in a pair cascade at the focus of the beams, that could be energetic enough to deplete them of their energy.

A more precise treatment of the problem should take into account the episodic emission of high-energy photons by the electrons, rather than assume a smooth classical trajectory. The pair yield would then be calculated by simulating the pair cascade that is initiated by the MeV photons in the field of the laser pulses. This may enhance the amount of pairs produced, because of the discrete energy loss of the electrons, which results in a higher energy spread [8].

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