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Prolific pair production with next generation lasers

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Introduction

Several experiments have reported the production of positrons using intense ($\sim 10^{20}\,\mathrm{W\,cm^{-2}}$) laser beams [1, 2, 3, 4]. In all cases, the laser was used to accelerate electrons, which subsequently initiated an electromagnetic cascade in a foil made of high-Z target material. The highest yield achieved so far is roughly 10^{11} positrons per laser pulse, which represents a small fraction (10^{-4}–10^{-5}) of the laser pulse energy. Much higher efficiencies are predicted for laser beams in which the electric field approaches the Schwinger value $E_{\mathrm{crit}} = 1.3\times10^{18}\,\mathrm{V\,m^{-1}}$, which is achieved at a laser intensity of roughly $10^{29}\,\mathrm{W\,cm^{-2}}$. However, even though this effect may be observable already at an intensity of $10^{26}\,\mathrm{W\,cm^{-2}}$[5], it is unlikely to be realizable in the near future.

Here and in a companion paper (Arka et al, these proceedings) we report on an alternative technique that may enable the conversion of a substantial fraction of the pulse energy into pairs at an intensity of around $10^{24}\,\mathrm{W\,cm^{-2}}$ [6, 7]. The technique is a three-step process: First, counter-propagating laser beams accelerate electrons in an under-dense plasma to several hundred MeV. These particles then radiate photons of comparable energy by non-linear Compton scattering of the laser photons. The $\sim 100\,\mathrm{MeV}$ photons then pair create by non-linear interaction with the laser photons. Steps two and three of this sequence have been studied in experiments at SLAC [8]. However, when all three steps operate in the focus of the laser beams, the number of pairs may grow exponentially and saturate only when a substantial fraction of the laser pulse energy has been converted into gamma-rays and pairs.

Electron acceleration

The classical trajectory of an electron picked up at rest by a linearly polarized vacuum wave is periodic in a reference frame that moves at speed $v_{\mathrm{ZMF}} = ca^2/(a^2+4)$ in the direction of propagation of the wave, where a is the Lorentz invariant strength parameter:

$$a = \frac{eE_0}{2\pi mc\nu_{\mathrm{laser}}} = 855\,I_{24}^{1/2}\lambda_{\mu\mathrm{m}} \qquad (1)$$

E_0 is the amplitude of the electric field of the wave, ν_{laser} its frequency, $\lambda_{\mu\mathrm{m}}$ its wavelength in microns and I_{24} is the laser intensity in units of $10^{24}\,\mathrm{W\,cm^{-2}}$. In this frame (the *Zero Momentum*

Frame) the electron executes the well-know figure-of-eight orbit with Lorentz factor roughly equal to a, if the wave is strong ($a \gg 1$). The radiation it emits is determined by the value of the Lorentz invariant parameter $\eta = \sqrt{(\mathrm{d}p^\mu/\mathrm{d}\tau)(\mathrm{d}p_\mu/\mathrm{d}\tau)}/mc$, where $p^\mu = (\gamma mc^2, \boldsymbol{p})$ is the electron four-momentum, and τ the proper time. In terms of the fields at the position of the particle

$$\eta \quad = \quad \frac{\gamma}{E_{\mathrm{crit}}}\left[(\boldsymbol{E}_\perp + \beta\boldsymbol{\mu}\wedge\boldsymbol{B})^2 + (\boldsymbol{\mu}\cdot\boldsymbol{E})^2/\gamma^2\right]^{1/2} \tag{2}$$

where $\boldsymbol{\mu} = \boldsymbol{p}/p$, $\beta = p/\gamma mc$, and $\boldsymbol{E}_\perp$ is the component of $\boldsymbol{E}$ perpendicular to $\boldsymbol{\mu}$. For a particle picked up at rest, η oscillates between the values 0 and $E_0/E_{\mathrm{crit}} = 2.1\times 10^{-3} I_{24}^{1/2}$.

This relatively low value of η can be attributed to the recoil experienced by the electron upon pick-up, as manifested by the high speed of the ZMF with respect to the lab. frame. If, however, the electron encounters counter-propagating beams, the ZMF is identical to the lab. frame, and a rough estimate using (2) gives $\eta \sim 4aE_0/E_{\mathrm{crit}} = 7.1 I_{24}\lambda_{\mu\mathrm{m}}$, where I_{24} refers to each linearly polarized beam separately. This estimate is, however, over-optimistic, partly because the trajectories are strongly influenced by radiation reaction [6], and partly because counter-propagating beams lead to much more complex trajectories [7]. An example of such a trajectory is shown in figure 1.

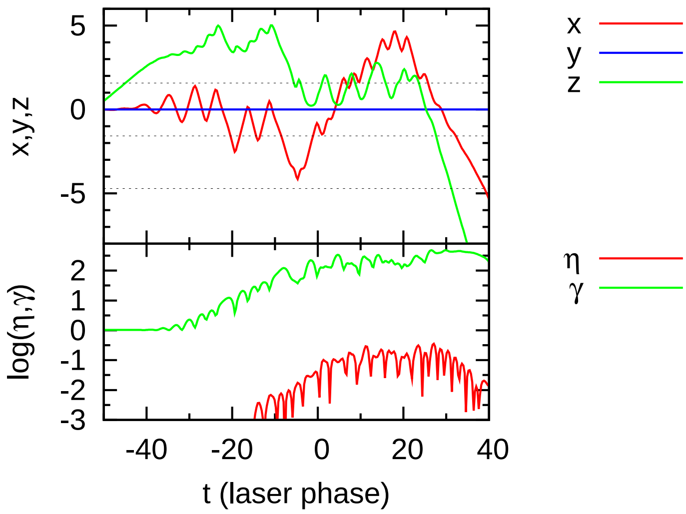

Figure 1: Trajectory of an electron picked up at rest at the leading edges of two linearly polarized, counter-propagating beams each of peak intensity $1.4\times 10^{23}\,\mathrm{W\,cm^{-2}}$ and wavelength 1μm, travelling along $\pm\hat{\boldsymbol{z}}$. The electron is accelerated to a Lorentz factor of $\gamma \approx a = 320$, but radiation reaction aligns its trajectory with the local field, resulting in $\eta < 0.4$

Gamma-ray emission and pair-creation

In a strong wave, $a \gg 1$ the coherence lengths and times associated with the processes of gamma-ray production by an electron and pair production by a gamma-ray are very short compared to the laser wavelength and period [9]. It is, therefore, a good approximation to treat the electromagnetic fields as constant during the interaction. Then, rather than non-linear Compton scattering and multi-photon Breit-Wheeler pair production, the processes are more appropriately called synchrotron radiation and single-photon pair production in a static field.

In the classical ($\eta \ll 1$), synchrotron ($a \gg 1$) regime, the characteristic photon energy is

$$\begin{aligned} h\nu &\approx \gamma^2 mc^2 E_0/E_{\rm crit} = \gamma^2 a h\nu_{\rm laser} \\ &= 775 I_{24}^{3/2} \lambda_{\mu{\rm m}}^2 \,{\rm MeV} \end{aligned} \tag{3}$$

corresponding, for the trajectory shown in figure 1, to 41 MeV. The spectrum of low frequency photons is of power-law type with intensity $\propto \nu^{1/3}$. At frequencies above the peak, the intensity cuts off exponentially. In the quantum regime $\eta \sim 1$, where a synchrotron photon carries off a significant fraction of the electron energy, the peak is shifted to slightly lower energies. The spectrum produced by an electron following the trajectory shown in figure 1 is shown in figure 2. The peak is at roughly 30 MeV, so that the classical estimate is reasonably accurate in this case.

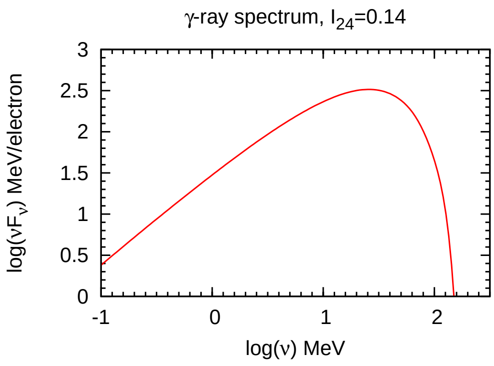

Figure 2: Gamma-rays produced by an electron following the trajectory shown in figure 1. For a total pulse energy of 150 J, roughly 10^{12} such electrons would convert a substantial fraction of the laser energy initially into ~ 30 MeV gamma-rays.

Depending on the point at which they are emitted, and on their direction of propagation, these photons may either escape from the laser beams without interaction, or may convert to pairs by absorbing multiple laser photons, (i.e., single-photon pair production in the strong quasi-static fields of the laser beams). The probability of this process is controlled by the photon equivalent of the electron parameter η defined in (2) (but conventionally with an additional factor of 2 in the denominator). For a photon of energy εmc^2, one estimates

$$\begin{aligned} \chi &\approx \varepsilon E_0/E_{\rm crit} \\ &= \varepsilon a h\nu_{\rm laser}/mc^2 \end{aligned} \tag{4}$$

Inserting the energy of the synchrotron photons produced by laser-accelerated electrons in the classical regime this becomes

$$\begin{aligned} \chi &\approx a^4 \left(\frac{h\nu_{\rm laser}}{mc^2}\right)^2 \\ &= 3.1 \left(I_{24}\lambda_{\mu{\rm m}}\right)^2 \end{aligned} \tag{5}$$

and one finds that the mean free path to conversion drops below 1 μm when the laser intensity exceeds roughly $4\times10^{23}\,{\rm W\,cm^{-2}}$ at a wavelength of one micron.

These estimates confirm that a pair avalanche can be expected in counter-propagating laser beams with $I_{24} \approx 1$. Because the pairs are created in regions of strong field, they are accelerated by the laser within a fraction of a laser period. Their number should, therefore, exponentiate until they are numerous enough to deplete the beam energy. However, these estimates ignore the effects of radiation reaction and do not take account of the geometry and polarization of the laser beams. In our companion paper (Arka et al, these proceedings) we present detailed results on the pair yield obtained by treating radiation reaction as a perturbation of the classical electron orbit, and using realistic models for the geometry of the counter-propagating beams.

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