Electron-positron pair production at high laser intensity

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Abstract: At laser intensities approaching 10^{24}Wcm^{-2}, plasma electrons interact directly with the laser fields to produce high energy gamma-rays and electron-positron pairs. These may be a dominant feature of experiments with the next generation of high power lasers.

Synchrotron radiation is a special case of photon emission by a moving particle deflected by static or low frequency electric or magnetic fields. This can be generalized to photon emission by electrons interacting with laser fields which themselves cause the electron to move relativistically. Next generation lasers should deliver intensities in the range of 10^{23}-10^{24}Wcm^{-2}. Electrons oscillate in the laser fields with Lorentz factors γ exceeding 100, and the laser electric field E exceeds 10^{15}Vm^{-1}. In this range of intensities, the product γE approaches the Schwinger electric field of 1.3x10^{18}Vm^{-1}. This is the condition for the interaction to produce electron-positron pairs as a parallel branch to production of high energy photons. However, it is not sufficient to simply place an initially stationary electron in the path of a high intensity laser beam. In this case, the electron is swept along in the direction of laser propagation, the E and vxB forces nearly cancel out, the electron is subject to little acceleration perpendicular to its velocity, and the threshold for pair creation is not reached. The condition for pair creation is that $\gamma|E+v\mathrm{x}B|_{\mathrm{perp}}$ should exceed the Schwinger field, where $\gamma|E+v\mathrm{x}B|_{\mathrm{perp}}$ is the component of the combined electric and magnetic forces perpendicular to the velocity of the electron.

The case of an electron in a single laser beam is analogous to the particle-particle interaction arising from an accelerated particle beam hitting a stationary target. An analogous benefit arises from the use of oppositely directed colliding beams[1,2]. In the laser case, the Schwinger condition can be met by placing the initially stationary electron between two counter-propagating high intensity laser beams. The electron remains approximately stationary in the direction of beam propagation while oscillating relativistically perpendicularly to this direction. The electromagnetic force has a strong component perpendicular to the instantaneous electron velocity. $\gamma|E+v\mathrm{x}B|_{\mathrm{perp}}$ is of the same order as γE, and the condition for pair creation is achieved. The simplest case to analyze is that of an electron oscillating at the B=0 node of a stationary wave formed by counter-propagating circularly polarized laser beams of equal amplitude. The electron follows a circular trajectory with the centripetal force provided by the laser electric field. At low intensities, the electron velocity is perpendicular to the electric field. However, at intensities above 10^{23}Wcm^{-2}, radiation reaction is strong and a component of the electric field is needed to combat the force due to radiation losses. In consequence, $\gamma|E+v\mathrm{x}B|_{\mathrm{perp}} < \gamma E$, and the laser intensity required for pair production is higher than that suggested simply by the value of γE. A further, secondary, process augments the rate of pair production particularly when the interaction is marginally close to the threshold for direct pair production. The trajectory of the high energy photons produced by the interaction is directed across the laser fields at arbitrary angles. Photons are not subject to the forces which tend to align electron velocities to make $\gamma|E+v\mathrm{x}B|_{\mathrm{perp}}$ less than γE. Hence the high energy photons interact with the laser fields to produce pairs. This secondary process dominates the direct process at intensities above 5x10^{23}Wcm^{-2}. At 10^{24}Wcm^{-2}, pairs are produced by the secondary process at a rate of about one pair per laser period per initial electron when the laser fields are strong over a distance of about one wavelength. At this intensity, an avalanche may occur in which electron-positron pairs interact with the laser beam to produce yet further pairs.

The most convenient experimental geometry might be to direct a single high intensity laser beam against a solid target. The reflected wave then provides a counter-propagating beam without the need for a separate laser beam. The reflected beam will contain harmonics which may or may not enhance the process of pair production. A further consideration is that even a solid target becomes relativistically transparent to laser beams at intensities between 10^{23}Wcm^{-2} and 10^{24}Wcm^{-2}. This introduces the possibility of stationary electromagnetic field structures in the solid which can only be analyzed by large scale simulation.

[1] AR Bell & JG Kirk, "Possibility of prolific pair production with high power lasers," Phys. Rev. Lett. **101** 200403 (2008)
[2] JG Kirk, AR Bell, I Arka, "Pair production in counter-propagating laser beams," Plasma Phys. Cont. Fusion **51** 085008 (2009)