Fundamental QED processes in ultra-intense laser field

A.M.Fedotov
National Research Nuclear University "Moskow Engineering Physics Institute"
E-mail: fedotov@cea.ru

Abstract. We expect that at laser intensities larger than $10^{24}W/cm^2$ laser-matter interaction will inevitably result in development of long chains (or showers) of quantum processes, with substantial e^-e^+ pair and hard photon production. These cascades of secondary processes open possibilities for arrangement of new kind of experiments with high-intensity lasers and should be incorporated into computer codes for numerical simulations of laser-matter interactions at high laser intensities.

It is well known that an ultrarelativistic electron colliding with an intense laser pulse emits hard photons which can create in turn a relativistic e^-e^+ pair. This can result in origination of chains of sequential acts of photon emission and pair production, or an electromagnetic cascade. This effect, essentially similar to Extensive Atmosphere Showers, besides being interesting per se, may accompany any act of interaction of high energy particles with an intense enough laser field and thus is of crucial importance for physics of extreme laser-matter interaction.

The intensity $I \geq 10^{24}\mathrm{W}/cm^2$ will be obtained at ELI with very short and tightly focused laser pulses. Nevertheless, at such intensities the length of formation for quantum processes under discussion is all the same much less than the characteristic length of variation of the laser field. Therefore such field can be treated locally as a constant homogeneous field.

Interaction of a single particle with a constant field is controlled by three parameters: the two field invariants

$$\mathcal{F} = \frac{\mathbf{E}^2-\mathbf{H}^2}{E_S^2}\,, \quad \mathcal{G} = \frac{\mathbf{E}\cdot\mathbf{H}}{E_S^2}\,, \tag{1}$$

and the dynamical parameter

$$\chi = \frac{e}{m^3}\sqrt{-(F_{\mu\nu}p^\nu)^2} = \frac{\sqrt{(\varepsilon\mathbf{E}+\mathbf{p}\times\mathbf{H})^2-(\mathbf{E}\cdot\mathbf{p})^2}}{mE_S}. \tag{2}$$

In (1) and (2) above, $E_S = \frac{m^2c^3}{e\hbar}$ denotes the critical QED field.

Provided that χ is the largest parameter among these three, any constant field looks as a crossed one ($\mathcal{F} = \mathcal{G} = 0$) [1]. The probabilities of different quantum processes in a crossed field were extensively studied in [1] and are well known, see also [2,3]. Note that if $\chi_e \sim 1$, then recoil in the process of photon emission becomes essential, while pair creation by a photon becomes possible if $\chi_\gamma \sim 1$.

To estimate multiplicities of e^-e^+ pairs and photons for a cascade initiated by a high-energy electron or hard photon colliding with a laser pulse, master equations

$$\frac{\partial f_\pm(\mathbf{p},t)}{\partial t} + \frac{\mathbf{p}}{\epsilon}\cdot\nabla f_\pm(\mathbf{p},t) \pm e\left(\mathbf{E}+\frac{\mathbf{p}}{\epsilon}\times\mathbf{H}\right)\cdot\frac{\partial f_\pm(\mathbf{p},t)}{\partial\mathbf{p}} = \int w_{rad}(\mathbf{p}-\mathbf{k}\to\mathbf{k})f_\pm(\mathbf{p}-\mathbf{k},t)\,d^3k - f_\pm(\mathbf{p},t)\int w_{rad}(\mathbf{p}\to\mathbf{k})\,d^3k + \int w_{cr}(\mathbf{k}\to\mathbf{p})f_\gamma(\mathbf{k},t)\,d^3k. \tag{3}$$

$$\frac{\partial f_\gamma(\mathbf{k},t)}{\partial t} + \frac{\mathbf{k}}{\omega}\cdot\nabla f_\gamma(\mathbf{k},t) = \int w_{rad}(\mathbf{p}\to\mathbf{k})[f_+(\mathbf{p},t)+f_-(\mathbf{p},t)]\,d^3p - f_\gamma(\mathbf{k},t)\int w_{cr}(\mathbf{k}\to\mathbf{p})\,d^3p. \tag{4}$$

for electron, positron and photon occupation numbers may be used. Up to now, we have succeeded in solving numerically these equations in the approximation of a one-dimensional cascade. The results, $N_{ee}\sim 2\chi_e$ and $N_\gamma \sim 10^2\chi_e$ per half-period of the laser, are in good agreement with the E144 SLAC experiment [4] ($\chi_e \sim 0.1$), where the effect of pair creation by hard photons in a laser field was observed for the first time. With ELI facility, long cascades can be realized even at the first stage. For example, in a head-on collision of an electron beam of 10^6 electrons with energy $\sim 50GeV$ and a laser beam of intensity $10^{23}W/cm^2$ about 10^9 e^-e^+ pairs and 50 billions of photons per shot will be produced. The outgoing particles will be of relatively small energy of about $50MeV$.

In agreement with [5], we expect that at laser intensities higher than $10^{24}W/cm^2$ the cascades will be initiated even by initially slow electrons, because at such intensities the electrons will be accelerated by the laser field itself and will acquire high enough energy for the time small as compared with the pulse duration [6]. To illustrate this possibility qualitatively, consider a toy model of an electron placed initially at rest in the uniformly rotating electric field. Let E_0 and Ω be the strength of the field and the frequency of its rotation. At $t \ll 2\pi/\Omega$ the growth of the electron energy can be estimated as $\varepsilon \sim eE_0 t$. An important point is that the angle between the directions of the field strength and the momentum of an electron also increases, $\theta = \Omega t/2$. As a result, the parameter χ_e increases as $\chi_e = eE_0\varepsilon\theta/m^3 \sim e^2E_0^2\Omega t^2/2m^3$ and may become of the order of unity at $t \sim t_{acc} = E_S/E_0\sqrt{m\Omega}$ if $t_{acc} \ll 2\pi/\Omega$, i.e. if $E_0 > E_S\sqrt{\Omega/m} \sim 10^{-3}E_S$. On the other hand, the probability of photon emission at $\chi_e \lesssim 1$ can be estimated by it's quasiclassical expression $W_{rad} = 1.44\alpha m^2\chi_e/\varepsilon$. It is easy to see that if $E_0 > E_* = \alpha E_S \sim 10^{-2}E_S$, then the total probability P_{rad} of radiation during the period t_{acc} is less then unity. This indicates that emission of hard photons with $\chi_\gamma \sim 1$ is quite probable if $E > E_*$. Such photons can produce a pair, however the resulting electron and positron will be generally slower than the initial one. But they can be accelerated again by the field as discussed above, so that the cascade can proceed until either all the charged particles will be pushed out of the focus by the ponderomotive potential or considerable depletion of the incoming laser pulse will occur.

Table 1. Multiplicity of self-developed cascades initiated by an initially slow electron versus the laser intensity.

$I, W/cm^2$	N_{ee}
$2.7 \cdot 10^{23}$	negligible and depends on initial conditions
$6.7 \cdot 10^{24}$	15
$2.7 \cdot 10^{25}$	7800
$1.1 \cdot 10^{26}$	$1.6 \cdot 10^{10}$
$6.7 \cdot 10^{26}$	$3.6 \cdot 10^{30}$

The results of preliminary numerical simulations are summarized in the Table 1. As it is seen from the Table 1, the cascades are expected to arise at the intensity level of $10^{24} W/cm^2$ and that at the intensity of about $10^{26} W/cm^2$ they will lead to depletion of laser pulse. The spontaneous pair creation from vacuum which can occur in the common focus of two collided pulses with total intensity $\sim 10^{27} W/cm^2$ [7] seems to be the natural mechanism of injection of slow electrons in the center of the focus. In such set-up it will be possible to observe the substantial transformation of the energy of collided laser pulses into macroscopic jets of lepton plasma and photons. In near future, we plan to analize QED cascades in ultra-intense laser field by more accurate 3D Monte-Carlo simulations [8].

References

[1] A. I. Nikishov and V. I. Ritus, Sov. Phys. JETP 19, 529 (1964); 19, 1191 (1964); 20, 757 (1965); 25, 1135 (1967).
[2] V. I. Ritus, in Issues in Intense-Field Quantum Electrodynamics, ed. by V. L. Ginzburg (Nova Science, Commack, 1987).
[3] V. B. Berestetskii, L. P. Pitaevskii, E. M. Lifshitz, *Quantum Electrodynamics*, Second Edition: Vol.4 (Oxford: Butterworth-Heinemann, 1982).
[4] D. L. Burke, *et al.*, PRL **79**, 1626 (1997).
[5] A. R. Bell, and J. G. Kirk, PRL **101**, 200403 (2008).
[6] A. Di Piazza, H. Gies, K.Z. Hatsagortsyan, T. Heinzl, A. Ilderton, C.H. Keitel, M. Marklund, S.D. Moustaizis, C. Müller, N.B. Narozhny, I. Ploumistakis, R. Schützhold, D. Symes and I. Tsohantjis, "QED cascades in intense laser fields", in "Report on the results of the Grand Challenges Meeting, 27-28 April 2009, Paris", Eds G. Korn and P. Antici, pp. 29-31, Paris, 2009.
[7] S. S. Bulanov, N. B. Narozhny, V. D. Mur, and V. S. Popov, JETP **102**, 9 (2006).
[8] A.M. Fedotov, N.B. Narozhny, G. Mourou, and G. Korn, to be published.