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New approaches on Laser Vacuum Breakdown for Pair Creation

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Abstract

The aim of this work is to present a complete and elaborated investigation on pair creation for two new kinds of experimental configurations using ultra-intense laser beams. The high pair production and ergonomic efficiency of the proposed experimental configurations may facilitate future designed experiments on laser-induced vacuum breakdown.

Introduction

Electron positron pair creation from strong fields-induced vacuum breakdown is one of outstanding importance non-linear QED phenomena [1-9]. Recently there is an increasing interest on experimental investigations concerning pair creation of (e^+, e^-) by ultra-intense laser beam interaction with vacuum due to new laser facilities installation [10, 11, 13].The theoretical treatment and the subsequent numerical analysis follow that of [12, 14, 15] where vacuum is treated as a two level quantum system under multi-photon resonance interaction with the laser beam.

In the first part, pair production is investigated using a configuration which utilizes high-energy photons generated by a laser based X-FEL in which the production and the acceleration of the high current electron beam are entirely produced by an ultra-intense laser beam.

In the second part, we will adapt our theoretical/numerical work [15, 17] to a novel experimental configuration, in which a high intensity laser beam interacts with a relativistic electron beam (REB), produced and accelerated by a high intensity laser system. Such a configuration is equivalent to the Stanford E144 experimental work [16] for pair creation. The numerical results presented concern the REB reference system for which the Lorentz transformation allows to increase the electric field of the laser beam by an important factor improving the efficiency of pair creation.

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Pair creation using a laser based X –FEL system

In the first configuration, we investigate, the use of a tabletop laser based X-ray Free Electron Laser for the (e^+, e^-) pair production from high energy photons laser beam interacting with vacuum. The proposed X-FEL will be operating by a relativistic electron beam produced and accelerated by the high intensity (~10^{20} - 10^{21} W/cm^2) ultra-short laser beam. The propagation of such a relativistic electron beam in a wiggler will produce the high energy photons of the x-ray beam necessary for the pair creation. The theoretical treatment and the numerical analysis follow the multiphoton resonant approximation, treating the vacuum as a two level quantum system and the equations describing the approximation are already presented in our previous work.[15, 17] where the number of produced pairs is given by $N_o = \frac{1}{4\pi^2}\frac{V\tau}{V_e}\frac{q\sqrt{q^2-1}}{m^2c^4}f_n^2$, with $f_n = \frac{E}{4p_y}\left(1-\frac{p_y^2}{E^2}\right)n\hbar\omega J_n\left(4\xi\frac{m}{E}\frac{p_y}{\hbar\omega}\right)$, and $q = \frac{E}{mc^2}$. The invariant parameter ξ is equal to the Work of electric field strength on a $\lambda_{Compton}$ / Photon energy, and is given by $\xi = \frac{e\cdot\mathcal{E}_o}{mc\omega}$ (In fact $\xi = 1/\gamma$, where γ, is in the pair production treatment of [5 -7], the equivalent of the Keldysh parameter). The selection of this parameter for the result presentation was done in order to emphasize the importance of the multiphoton process for the pair creation and allow estimations for the necessary electric field (or laser intensity values for pair observation).

For the application we consider an electron beam with energy up to 1GeV and total charge up to 1 nC, which can produce x-ray photons with energy of 1.909 keV. We assume 10% energy conversion efficiency from the laser beam to the x-ray with a pulse duration τ =100 fs and a focal spot of the main laser beam of σ = 100nm. This effect takes place in interaction volume V given by $V=\sigma^2(0.1\lambda)\tau$. Similar numerical estimations were carried out for other energy values, specifically for electron beam energy of 400 MeV and 200 MeV. Using the above parameters the efficiency of the resonance multiphoton approximation was tested, following the methodology and the mathematical analysis from our previous work[15, 17]. Fig. 1 presents the created pair number vs. the parameter ξ for the three mentioned energies. The choice of plotting vs. the parameter ξ, is justifiable since it depends from the electric field strength and photon energy and thus allowing to investigate the dependence of N_0 on both of these physical quantities. For any future experimental verification these plots are important as they show the range of applicability of this approximation. By adjusting the photon energy and the electric field strength, one can estimate the produced e^+ e^- pairs, for the corresponding value of ξ, from the plot. As one can observe the curves have ending points dictated by energy conservation considerations.

The curves verify the fact that we are studying multiphoton processes, and as we can observe the efficiency of pair creation can reach up to 10^9 pairs depending the electron beam energy. Such results are significant and strongly suggest the possible use of this configuration, for experimental observation of resonance approximation.

Pair creation using a configuration analogous to the E144 experiment.

The second proposed configuration is based on the E144 experiment that took place on SLAC [16] and was the first experimental verification of electron positron pair production due to non-linear photon – photon interaction. A number of 175 ± 13 positrons were measured for 21962 laser shots corresponding to 5.1 multiphoton order.

Our proposed configuration consists of two steps. On the first step a relativistic electron beam is produced using a high intensity, ultra sort laser beam. On the second step this electron beam interacts with a second ultra-high intensity laser beam (photon energy = 1eV) from the same laser system. We consider the energy of the electron beam to be 1 GeV, created by a laser beam with 10^{20} W/cm^2. On the electron's reference frame, the Lorenz transformed electric field is $\mathcal{E}^* = \gamma_L \mathcal{E}_{laserlab} = \gamma_L \sqrt{\mu_o c I}$, and the photon energy $E^*_{photons} = \gamma_L E_{photons}$ where $\gamma_L = \dfrac{E_{e-beam}}{m_e c^2}$ is the Lorenz relativistic factor. With $E_{e\text{-beam}}$= 1 GeV, $E^*_{photons} = 1.956 keV$ and $\mathcal{E}^* \sim 10^{14} V/cm$. Applying the same analysis as in [15, 17] we conclude that the efficiency of multiphoton pair production using this configuration, is very high leading to Fig.2 which summarizes our results for three energies of electron beam (1 GeV, 400 MeV, and 200 MeV).

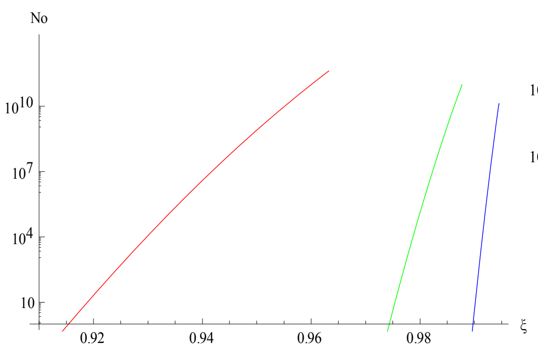

Fig. 1

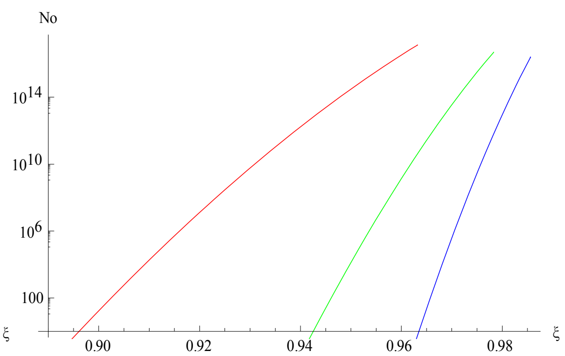

Fig. 2

Fig 1. Log plot of number No of created $e^+ e^-$ pairs versus ξ for 1GeV (Red), 400 MeV (Green), and 200 MeV (Blue) Laser X –FEL configuration. Fig 2 Log plot of number No of created $e^+ e^-$ pairs versus ξ for 1GeV (Red), 400 MeV (Green), and 200 MeV (Blue) E144 experiment equivalent configuration.

Conclusion

For this work, we investigate theoretically two configurations based on high intensity laser pair creation. The first concern the uses of a small scale X-FEL system and the other describe an analogous to the E144 experimental configuration. Both of them appear to have very satisfying efficiency and meet our targets of proposing new methods that do not require special facilities using huge accelerators, but can be carried out on small scale designed experiments. Furthermore, use of available values for the parameters on which our configurations depend ensures that the results are realistic. The optimal results depending on the laser parameters are of the order of 10^{12} pairs for the first configuration and 10^{15} for the second.

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