Numerical comparison of Popov and Breit - Wheeler schemes on laser vacuum breakdown for pair creation

Ioannis Ploumistakis[(1)*], S.D. Moustaizis[(1)], I. Tsohantjis[(2)]

[(1)] Technical University of Crete, Laboratory of Matter Structure and Laser Physics, Chania, Crete, Greece

[(2)] University of Athens Physics Department, Faculty of Nuclear and Particle Physics, Athens, Greece

**email: iploumistakis@isc.tuc.gr*

Introduction

- Next generation of ultra intense laser facilities (ELI, ORION) has risen the interest for experimental verification of e^+e^- pair creation from vacuum.
- Such facilities are expected using specific Experimental Setups to reach the critical field strength required for pair creation in the near future. $\mathcal{E}_c = 1.3 \times 10^{18} V/m$
- The aim of this presentation is to examine possible schemes for experimental verification and compare their efficiency in terms of created pair number.
- We will focus to schemes that utilize the Popov model and Breit-Wheeler mechanism.

Popov's theoretical model

- Popov's theoretical treatment [1] which is based on multiphoton processes is used for a setup analogous to the E144 experiment.

- A high intensity ultrashort laser beam ($I \sim 10^{24}$ W/cm^2 , $\tau \sim 20 - 50$ fs) of ω = 1 eV is used to accelerate a electron beam (of 1 nCb charge) to a range of energies up to 100 GeV.

- In the electron's frame of reference the photons have energy $\omega^* = \gamma_L \omega$ and electric field strength $\mathcal{E}^* = \gamma_L \mathcal{E}\,(V/m)$

γ_L is the Lorentz factor

Popov model

Popov's model is described by the following formulas [1]

$$w_p = \sum_{n>n_0} w_n \qquad \boxed{w_n = \frac{(2s+1)m^4}{4\pi^2}\left(\frac{\hbar\omega}{mc^2}\right)^{1/2}\left(\frac{n-v}{\Delta_2}\right)^{1/2} J_n \exp\left[-\frac{2mc^2}{\hbar\omega}f - \frac{2f_1}{\Delta_1}(n-v)\right]}$$

$$V_e = \hbar^4/m^4c^5 = 7{,}4\times10^{-59}\, m^3 s \quad \gamma = mc\omega/e\mathcal{E} = \hbar\omega\mathcal{E}_c/mc^2\mathcal{E} \quad n_0 = mc^2\Delta/\hbar\omega$$

$$\Delta = \frac{4}{\pi}\frac{\sqrt{1+\gamma^2}}{\gamma}\mathrm{E}\left(\frac{1}{1+\gamma^2}\right) \quad \Delta_1 = \frac{2}{\pi}\frac{\gamma}{\sqrt{1+\gamma^2}}\mathrm{K}\left(\frac{1}{1+\gamma^2}\right) \quad \Delta_2 = \frac{2}{\pi}\frac{\gamma}{\sqrt{1+\gamma^2}}\mathrm{E}\left(\frac{1}{1+\gamma^2}\right) \quad v = \frac{\Delta mc^2}{\hbar\omega}$$

$$J_n = \int_0^1 dx e^{\lambda(n-v)x^2}\left[1+\sigma(-1)^n\cos\xi_n x\right] \quad \lambda = 2\left(\frac{f_1}{\Delta_1} - \frac{f_2}{\Delta_2}\right) \quad \xi_n = 2\gamma\psi(\gamma)\sqrt{\frac{(n-v)mc^2}{\hbar\omega}}$$

$$f_1 = \frac{\pi\gamma}{2\left(1+\gamma^2\right)^{1/2}} \quad f = \frac{\pi\gamma}{1+\left(1+\gamma^2\right)^{1/2}} \quad f_2 = \frac{\pi\gamma^2}{2\left(1+\gamma^2\right)^{1/2}}$$

Using the above formulas for the parameters mentioned in the previous slide Figure 2 is obtained, which describes the created pair number versus the electric field strength.[5]

Pair creation efficiency and crossing points

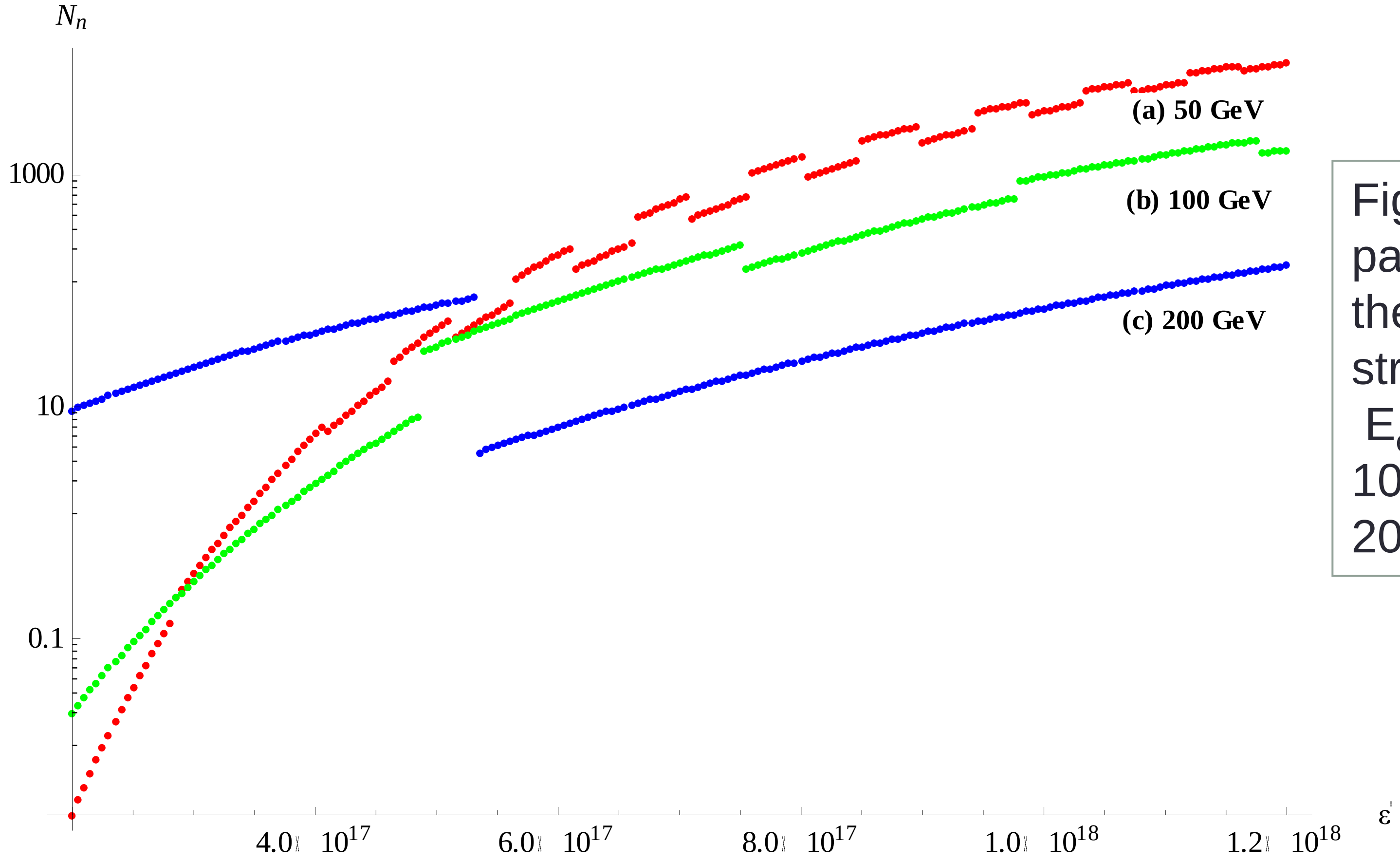


Figure 1. Created pair number versus the electric field strength for $E_{e\text{-}beam}$=50(red), 100GeV(green), 200 GeV(blue)

The full formula can provide better estimations concerning the efficiency of the created pairs, especially including the area of γ = 1.

Pair creation efficiency and crossing points (II)

- An interesting observation the existence of an area that curves cross. These crossing points show that for electric field strength values above the range where the crossing points are, higher multiphoton orders can result to higher creation efficiency. The interest for high multiphoton order is obvious for the pair production efficiency.

- Also our results show the dependence of efficiency on having an odd or even multiphoton order.

- As E increases, $[n_0 + 1]$, takes even and odd values and thus because of the term $\left[1+\sigma(-1)^n \cos \xi_n x\right]$ in J_n, w_n oscillates accordingly, as can be seen in Figure 2.

Breit-Wheeler setups for pair production

- Another proposed mechanism for pair production is based on Breit-Wheeler model [1]
- This mechanism can be examined by two proposed experimental setups as can be seen in bibliography [3],[4].

- Breit-Wheeler experimental setup (setup 1) consists of two successive physical processes. At the first physical process the interaction of a high intensity laser beam with an electron beam produces γ photons. At the second physical process the γ photon beam interacts with the photons of the laser beam producing e^+e^- pairs. (see Figure 2).

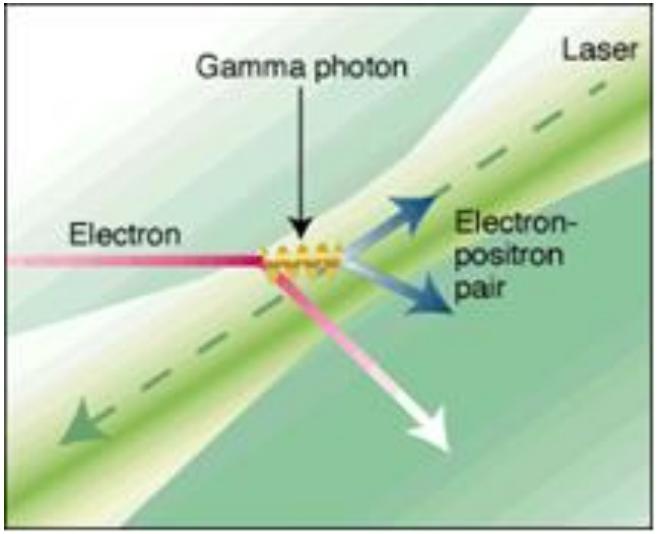


Figure 2. Schematic representation of BW scheme

Breit-Wheeler process for pair production

To estimate the created pairs number the following formula can be used

$$W = 2\rho_{\omega}\rho_{\omega'}\sigma_{BW} = 2\pi r_0^2 \frac{m^2}{\omega\omega'}\rho_{\omega}\rho_{\omega'}\left\{\left(2+\frac{2m^2}{\omega\omega'}-\frac{4}{(\omega\omega')^2}\right)\tanh^{-1}\sqrt{1-\frac{m^2}{\omega\omega'}}-\sqrt{1-\frac{m^2}{\omega\omega'}}\left(1+\frac{m^2}{\omega\omega'}\right)\right\}$$

where W is the pair number per unit volume and unit time ρ_{ω} and $\rho_{\omega'}$ are the number densities (photons/m^3) for the γ photons and x ray photons respectively. m is the electron mass and ω, ω' the photon energies in eV and r_0 is the classical electron radius 2.818 x10^{-15} m.

Breit-Wheeler experimental Setup II for pair production

- Another experimental setup was proposed recently by O.J Pike et. all.[3].
- A high energy electron beam produces high energy gamma photons by interaction with a solid target. The gamma photon beam interacts with x-ray photons produced by laser irradiation of a hohlraum .
- This setup handles γ photon and x-ray photon creation independently in contrast with the Setup I. Thus it can optimize γ and x photon numbers

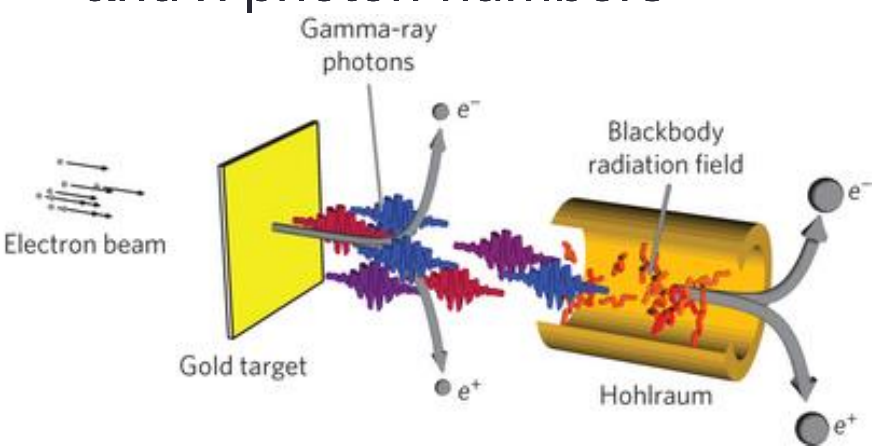
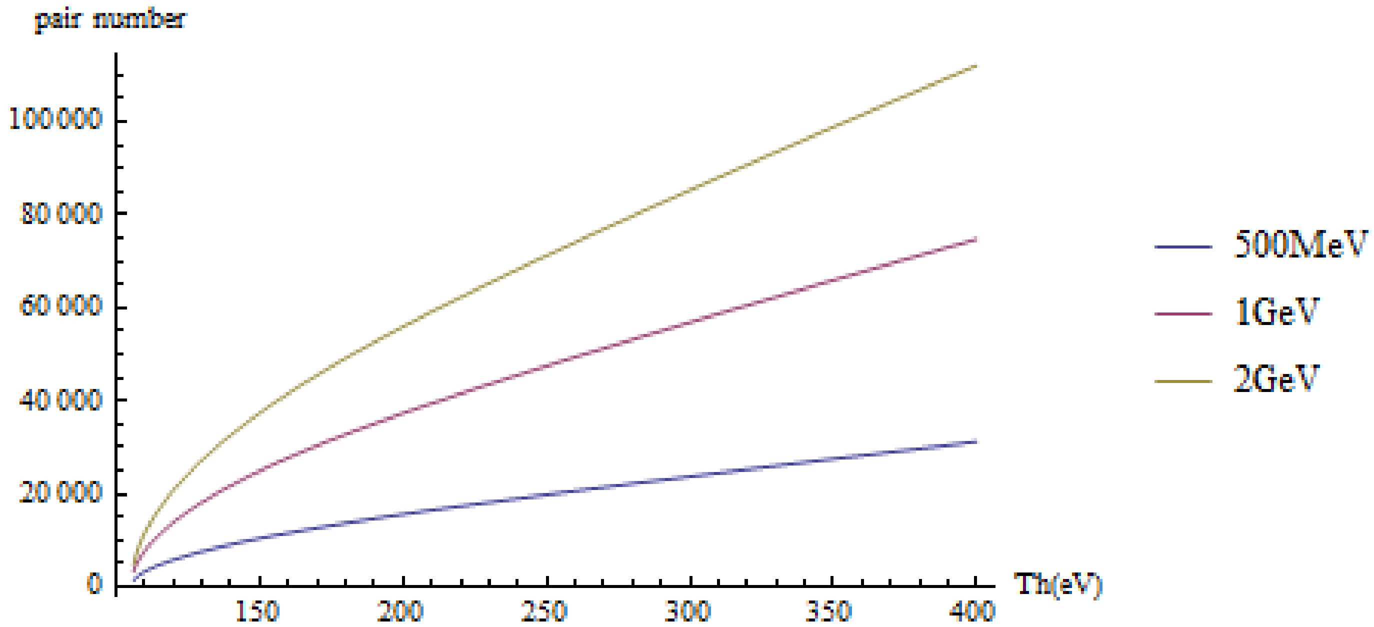


Figure 2. Schematic of the proposed scheme as seen in Nature Photonics

Breit-Wheeler experimental <u>Setup II</u> for pair production

- Using the parameters presented in [3] and the formula for BW pair creation we examined the efficiency on a BW scheme.
- We considered an electron beam containing 10^9 electrons and E-beam energy 500 MeV, 1 GeV and 2 GeV that interacts with a target with 3mm thickness. The hohlraum length is L_h=1cm, its radius R_h=5 mm and its temperature is within the range of 100 and 400 eV.
- Using the above parameters we conclude that our estimates are in good agreement with [3].



Conclusions

- We presented the pair production efficiency for two theoretical models and different experimental setups
- The first scheme is an analogous to E144 scheme using Popov's treatment.
- Afterwards a scheme based on Breit Wheeler mechanism was examined. Especially for the case of setup described in [3] its strong points lie to the fact that can achieve high efficiency in terms of photon numbers both γ and x.
- However the hohlraum heating for example requires a laser system with characteristics equivalent to the NIF system.
- For realistic temperatures of hohlraum of the order of 200 eV the number of pair production is 10^3 per laser shot.

Conclusions (II)

- The temperature of 300 eV or higher can be achieved using NIF laser system with 1 MJ total laser beam energy or with equivalent system with hundreds of kJ energy in the laser beam, but with smaller dimensions for the hohlraum which corresponds to a smaller number of x-ray photon production and consequently less than 10^3 pairs produced per laser shot.]

- The Popov model presents higher efficiency than the Breit-Wheeler model as for the same values of the laser intensity and under conditions described in our previous paper [5,6] the number of pair generation approaches the value of 10^6. This is due to higher production cross sections.

References

1. V.S. Popov, JETP Lett. 13, 185 (1971); Sov. Phys. JETP 34, 709 (1972); Sov. Phys. JETP 35, 659 (1972); V.S. Popov and M. S. Marinov, Sov. J. Nucl. Phys.16, 449 (1973) ; JETP Lett. 18, 255 (1974); Sov. J. Nucl. Phys., 19, 584 (1974).
2. Breit, G. & Wheeler, J. A. Collision of two light quanta. Phys. Rev. 46, 1087–1091 (1934).
3. O. J. Pike, F. Mackenroth, E. G. Hill & S. J. Rose A photon–photon collider in a vacuum hohlraum, Nature Photonics 8, 434–436 (2014).
4. Burke, D. L. *et al*. Positron production in multiphoton light-by-light scattering. Phys. Rev. Lett. 79, 1626–1629 (1997).
5. I. Ploumistakis, S. D. Moustaizis, and I. Tsohantjis, Numerical investigation and potential tunability scheme on *e+e-* and π+π- stimulated pair creation from vacuum using high intensity laser beams**.** Under publication in High Power Laser Science and Engineering.
6. I. Tsohantjis, S. D. Moustaizis, I. Ploumistakis Physics Letters B Volume 650 (2007).