Gamma Photons and electron-pairs Generation estimation for collision of PW-class Laser and electron beams

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Abstract. After the proposal of the concept of CPA techniques, the laser intensity has boosted dramatically since then. As the focusing intensity of the laser beam reaches the order above 10^{23} W/cm^2 for multiple PW laser facilities, the laser material interaction enters the QED regime, where the gamma photons generation and electrons-positron pairs generation can be realized. This paper provides an overview of the current research in the field of electrodynamics about laser intensities and electron generation. Basic theories of the generation of e and e^- pair and photons are introduced. The history of the development of major laser facilities with high-laser intensities is introduced, and the laser facilities are compared and discuss in terms of the electron generations. The results are further compared with the PIC simulation and typical generation scenarios are demonstrated. Potential limits are mentioned as the drawbacks of the models. Overall, these results shed light on guiding further exploration of laser-plasma interactions in the extremely strong intensity laser beam.

Keywords: high-intensity laser; electron generation; photon collision.

1. Introduction

After the invention of the concept of chipped pulse amplification (which wonned the Nobel physics prize in 2018), the laser intensity has been growth sharply in recent years. Contemporarily, the application of ultra-intensity laser has been expanded as well as further explored and proposed, such as the application of laser and electron beam in high intensity particle physics. Moreover, the lasers technology serves as one powerful sources of electron magnetic radiation [1].

The tested maximum intensity of PW-class laser achieves $10^{23}\,W/cm^2$ under laboratory condition, while PW-class laser facilities can achieve the intensity of $10^{23}W/cm^2$ ideally [2]. With such laser with strong intensity, scientists found out that these lasers can be used for the application of detecting regime of interaction of charged particles with radiation, and the properties of vacuum [1]. There can possibly be highly non-linear physics occurring one there is a laser matter interaction. In other words, laser-matter interaction enters the field of near QED regime as it is exposed under strong laser field [3, 4].

Nowadays, institutes around the world are analyzing and developing the use of high intensity laser with output over one petawatt (PW) [5]. Some laser intensity over $10^{22}\,W/cm^2$, e.g., the HERCULES laser [6], the Texas Petawatt [7], the Shanghai Ultrafast Laser facility (SULF) [8]. Out of these facilities, CoReLs PW laser achieved an intensity of $5 \times 10^{22}\,W/cm^2$. Yet scientist is giving more effort on enhancing the laser intensity, this include Apollon [9], which has output of 10 PW and beyond, is under construction.

Analyzing such high intensity lasers help scientists on exploring the interaction of electrodynamics, acceleration of electrons and ions [5]. Nowadays, the recorded upper limit of the intensity comes from Korea, where scholars develop the PW-class laser with intensity over $10^{23}\,W/cm^2$ [5].

The Study of high intensity laser and electron beams are crucial for the field of electrodynamics. The article reports the current study of particles generation under the collision of laser and electron beams, along with the fundamental concepts of the Feynman diagram and the formula. By comparing the different intensities of the laser, we estimate the generation of electrons. This serves to provide later generation the relevant knowledge and research in this field and provides potential research directions for electrodynamics.

2. Models of the Reaction Chanel

2.1. Non-linear Compton Scattering

In this section, we will review the principles of generating γ rays and e and e^- pair. Compton scattering is a fundamental process that energy photon colliders need to go through. Compton effect assumes that photons, like physical particles such as electrons and protons, not only have energy, but also have momentum. In the process of collision, both energy and momentum are conserved. After the short wavelength electromagnetic radiation is emitted into the material and scattered, in the scattering wave, in addition to the wave of the original wavelength, there is also a wave with an increased wavelength. The larger the atomic number of the scatterer, the smaller the ratio of the intensity of the wavelength increasing part of the scattering wave to the intensity of the original wavelength part [10]. A sketch of the Feynman diagram for this process is shown in Fig. 1.

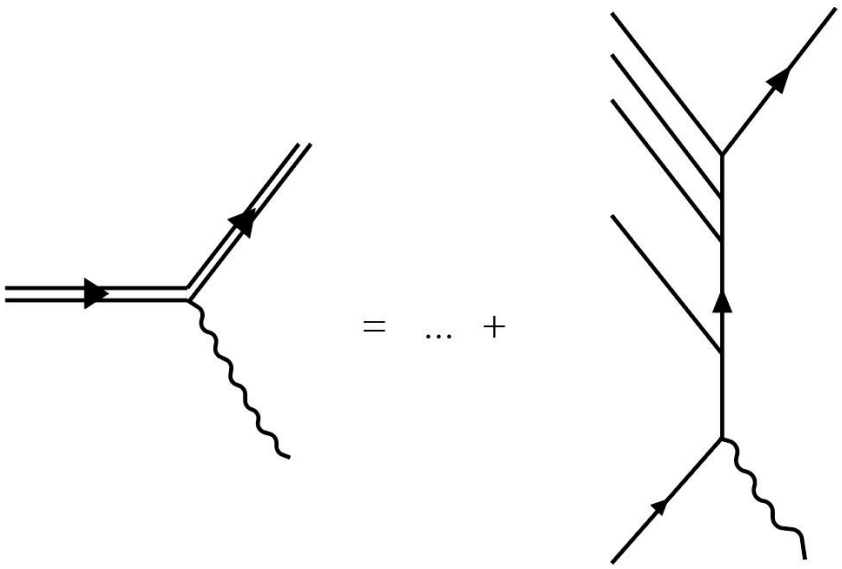


Fig. 1 Non-Linear Compton Effect

When a density of laser photons is very high, the simultaneous interaction of electrons with several laser photons might cause the processes in the conversion area to become nonlinear. The electromagnetic wave's interaction with electrons and positrons can be represented by the intensity parameter $\Im$ [10, 11]. The reaction formula is given as follows:

$$e(p) + n\gamma(k_0) \rightarrow e(p') + \gamma(k), n \geq 1 \quad (1)$$

$$\gamma(k) + sy(k_0) + e^+(p_+) + e^-(p_-), s \geq 1 \quad (2)$$

$$m^2 \rightarrow m_*^2 = m^2(1 + \Im^2) \quad (3)$$

$$\Im^2 = n_\gamma \left(\frac{4\pi}{m^2\omega_0}\right) = -\frac{e^2a^2}{m^2} \quad (4)$$

Here, one uses n_γ to represents the wave's photon density, ω_0 is the total energy of the photons, α is the amplitude of the classical 4-potential of electromagnetic wave, e is the charge ss of the electron, and m is the mass of the electron [11]. One can use a differential equation to analyze the collision between electron and the high intensity laser waves.

$$\frac{d\sigma}{dy}(\lambda, \lambda_e, \lambda', \lambda'_e) =$$

$$\frac{\pi\alpha^2}{2xm^2\Im^2}\sum_{n=1}^{\infty}\{(1+\lambda_e\lambda'_e)F_{1n} + \lambda(\lambda_e+\lambda'_e)F_{2n} + \lambda'(\lambda F_{3n} + \lambda_e F_{4n}) + \lambda_e\lambda'_e F_{5n}\} \quad (5)$$

This differential equation demonstrates the energy dependence of the difference cross-section of process as a function of $y = \omega/\varepsilon$ [11].

2.2. Nonlinear Breit–Wheeler process

As an inversed/mirror process of above condition, electron–positron (EP) pairs can be created through the Breit–Wheeler process. As this is also the most optical way in achieving, which has been verified in SLAC based on the collision of focusing lasers and focused energetic electron beam. For extremely strong laser, the multiple photons serve as background field. In this case, the process become to the non-linear forms so that the EP pairs is produced by collision of heave photons (gamma photons) to the field background (multiple laser photons) [12, 13]. A typical sketch of the process is presented in Fig. 2. This process can take the form of

$$\gamma + n\,\omega \rightarrow e + e^- \quad (6)$$

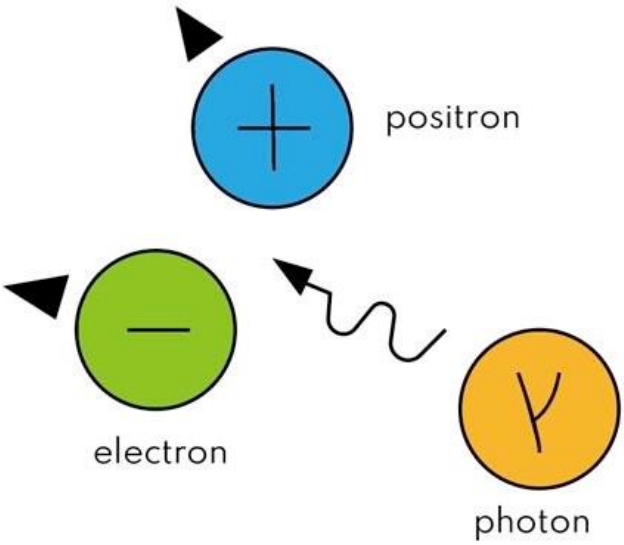


Fig. 2 The Feynman diagram of Breit Wheeler process for the generation of electron positron.

3. Results of the estimated electron generation based on intensity of the lasers.

In this section, this study will discuss the simulation of γ rays and e and e^- pairs generations based on scientists 'works. A two-laser collision scenario is proposed where the obtained results are presented in Table. 1 [14]. The Table I discusses the average energy of the γ photons and positrons, the number of particles produced during the simulation, and the laser conversion efficiency. The average energy is similar in all the simulation data as shown in Table 1, suggesting that the average energy of the particle correlates to the laser intensity. The positrons' energy in the scenario with higher comparative ratio (e.g., achieving by using plasma mirror) and compressor duration can be significantly increased, because the positrons continue to accelerate as they propagate after being

trapped by the reflected field. The Table I summarizes the simulation results under different conditions.

Table. 1 Simulation Results of different initial settings.

Setup	E_γ [MeV]	N_γ	η_γ	E_{EP} [MeV]	N_{EP} (nC/μm)	η_{EP}
Case1 τ=15fs	14	6.4×10^{18}	0.24%	240	0.09	0.01%
Case1 τ=150fs	12	1.1×10^{20}	0.2%	200	3.28	0.04%
Case2 τ=15fs	20	1.36×10^{19}	0.23%	230	1.4	0.2%
Case2 τ=150fs	10	1.0×10^{20}	0.2%	200	2	0.03%

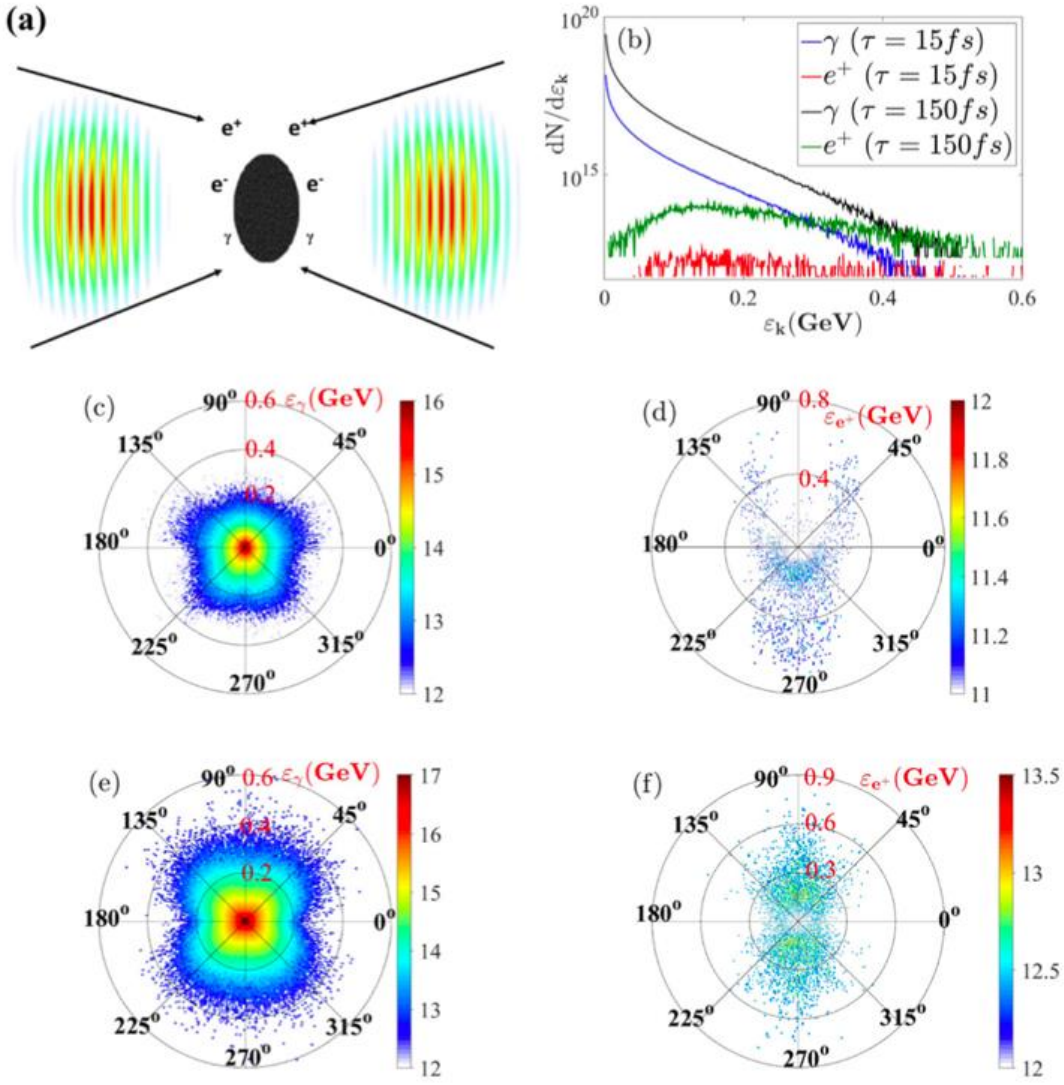


Fig. 3 Simulation results for the gamma ray and EP pairs energy spectrum as well as spatial distribution.

The quantity of initial electrons until the standing wave's peak intensity is attained depends on the optimal initial target density for a specific laser pulse. The maximum number of positrons produced occurs in the scenario when two colliding laser pulses engage with a target with an initial density of 50 ncr (200 ncr) (150 fs). Given that both pulses' peak intensities are equivalent, the longer pulse has a higher energy content and successfully generates positrons. For each seed electron in this scenario,

0.01 positrons are generated; however, the quantity is ten times smaller for short pulses. With a longer laser pulse, a greater number of photons and positrons are generated in absolute terms (Seen from the Table. 1). This results from both the four times greater quantity of seed particles and the formed standing wave's substantially longer duration. As a result, in the long-pulse case, a higher percentage of the laser energy is transformed into photons and positrons. The likelihood of pair creation is influenced by the strength of the electric field, photon momentum, and mutual orientation [14]. The simulated spectrum as well as the angular distribution of the gamma rays and EP pairs are illustrated in Fig. 3.

4. Limitations

In this section, this research will be analyzing the limits of the models in the previous section. It should be noted that all the results are come from the PIC simulations instead of the experiment investigations. Hence, the models for generation play a pretty important role for the accuracy for the whole results. As a matter of fact, the models make loss of assumptions, so that there will be problems in the theoretical calculation. For example, the local-constant-field approximation (LCFA) is used in the models, where the field is considered as a constant field during interaction, i.e., the generated photons will not gain any energy directly from the laser pulse via the reaction. In this case, there might be some errors when calculation, though this is a common tool used to analyze the strong field QED. When the energy produced by non-linear scattering and non-linear Breit Wheeler process exceeds a limit, the approximation is no longer applicable, i.e., break the non-presentative framework. In addition, Monte-Carlo algorithm is used in the PIC simulation. This is a randomed algorithm that produced results with random errors. The stochastic feature of QED might lead to the uncertain results that has no physical feature. Thus, the results of the discussed PIC simulation have a certain degree of randomness. In the future, further models and better calculation algorithms should be proposed to address the issue mentioned above. Meanwhile, it should be witnessed that the experiments can offer some improvements suggestions to the revision of the models.

5. Conclusion

In summary, this paper investigates and discusses the high energy gamma photons as well as the electron-positron pairs based on the ultra-intensity laser beams. To be specific, the basic knowledge and principles of laser collisions are introduced and derived directly to give a first impression. By analyzing the interaction of the high-energy electron beam and the high-intensity laser pulse, along with the non-linear Compton effect and the non-linear Breit wheeler process, we discuss the simulation of the generation of γ photons and electrons pairs. The discussed results may serve on helping to design the future experiment, and the results of the simulation can be used as a reference for the future study of laser facility. Overall, these results offer a guideline for future scenarios design and analytical model improvements for strong field QED.

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