Gamma ray and Electron- positron pairs generation based on ultra-intensity and ultra-short laser

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Abstract. With the rapid development of the ultra-short and ultra-intensity laser techniques, the intensity of laser has reached 10^{23}W/cm^2, which offers a tool to investigate the laser matter interaction in QED regime. On this basis, it is feasible to generate gamma rays and electron positron pairs in terms of strong field laser plasma interaction. In this paper, the state-of-art configuration and schemes for above particles generation are discussed. Besides, the limitations as well as future direction are also analysed. These results shed light on further exploration of laser-plasma phenomena in strong field physics.

Keywords: A Electron-Positron Pairs; Gamma ray; Ultra-intensity Laser.

1. Introduction

The study of rapid processes in matter necessitates the use of ultra-short laser pulses with duration from femtosecond to attosecond. Numerous techniques have been applied to obtain lasers with short pulses (e.g., the so-called Q-switching, mode-locking, dye lasers). Morey and his student Strickland devised the chirped pulse amplification (CPA) technology in 1985 during working at the University of Rochester, which pave a path to compress the laser into much higher intensity and shorter duration. The following sections discuss the technical aspects of chirped pulse amplification. After stretching the ultrashort laser pulses by orders of magnitude in time, the power peak is lowered by orders of magnitude. It is then magnified securely within the laser material. Finally, time is compressed to its original length, and the amplified power peak becomes extremely powerful [1]. Additionally, chirped pulse amplification technology generates ultrashort lasers appropriate for industrial and medical applications, particularly those requiring high precision.

Extremely intense electromagnetic fields (E>10^{14}V/m) are created by high-power lasers operating at intensity larger than 10^{21}W/cm^2. Within a single laser cycle, these fields can accelerate electrons to the point where the majority of the energy is emitted as gamma rays [2].

Gamma-ray photons are mostly released into a vortex that may be estimated as entirely forward for the relativistic electrons studied here. An electron's rate at which it emits gamma-rays when there is a constant magnetic field around it, where the analytical model for spin averaged case and condition of $cB \ll E_s$ is given as follows

$$\frac{d^2N_\gamma}{d\chi dt} = \frac{\sqrt{3}\alpha_f}{\lambda_c}\frac{cB}{E_s}\frac{F(\eta,\chi)}{\chi} \tag{1}$$

The energy of an electron is $\gamma m_e c^2$ parameterized by n and the energy of a photon is parameterized by x. According to Erber and Sokolov and Ternov, λ is the wavelength and $F(n,x)$ is the quantum-corrected. The instantaneous power over $F(n,x)$ emitted can be described as

$$P = \left(\frac{4\pi m_e c^3}{3\lambda_c}\right)\alpha_f\eta^2 g(\eta) = P_c g(\eta) \tag{2}$$

where P_c represents for the power in classical descriptions and the $g(\eta)$ satisfies the form of

$$g(\eta) = [1 + 4.8(1+\eta)\ln(1+1.7\eta) + 2.44\eta^2]^{-\frac{2}{3}} \tag{3}$$

P_c occurs when $f(n,x)$ is adjusted in a manner that departs from the conventional synchrotron spectrum. It's worth noting that it results in a fivefold reduction in P when $g(n) = 0.2$. According to the Eq. (3), it is clearly clarified that how gamma-ray photons and electron-positron pairs generation (both of which are included in the laser plasma simulation code) can be modelled.

The electromagnetic field is made up of parts with high and low frequencies. Infrasonic high fields, dubbed "laser fields," change at the same level as the wavelength of the laser. The laser field are coherent states that stay the same when QED interacts with them. Maxwell's equations are used to figure out how these fields work. On this length scale, smoothed plasma charges and currents are utilized to accomplish this. Baier and Katkov demonstrate that this approach can include electron, and the elevated component of the electromagnetic field. Particles flow between point-like quantum electrodynamic interactions in this manner [2].

The rest part of the paper is organized as follows. The Sec. 2 mainly discussed theoretical basis of strong-field QED in laser-generated Gamma ray and positron-electron pairs. Subsequently, the Sec. 3 will give some brief analysis of the generation of electron-positron pairs under actual lasers. Afterwards, the Sec. 4 presents the PIC simulation and some resulting data. Then, the limitations and defects of the state-of-art scenarios are analysed and the future prospects are also proposed in the Sec. 5 accordingly. Eventually, a brief summary will be given in the Sec 6.

2. Strong-field QED (SFQED)

As long as there is an ultra-intense ultra-short laser-generated outside field, the QED process will happen. New discoveries in physics are frequently produced by investigating new parameter regimes, according to a well-established paradigm. Energy is what moves the focus of the experiments from the mundane macroscopic field to the high-energy physics., is arguably the most crucial quantity. Temperature, density, and pressure are some of the other significant characteristics that may be modified. Many of the lectures at this conference have included geometry as a key component of the Casimir effect's boundary requirements. Finally, manipulating the amplitude of an external field may be investigated, since this may have a substantial impact on the mechanics of spin and superconductors in their magnetic state [3].

$$z[A] = \int D_a D_\psi D_{\bar{\psi}}\, \mathrm{e}^{i\{S_{QED}[a,\psi,\bar{\psi}]-e(A,j)\}} \tag{4}$$

Here, S_{QED} is the typical quantum electrodynamics action that is dependent on the fermion fields ψ and $\bar{\psi}$ and a_μ is the oscillating quantum field summed over in the route integration. The external field A, on the other hand, does not have its own dynamics; its only purpose is to couple to the fermionic current $j\mu = \psi\gamma\mu\bar{\psi}$. In other words, we approximate the lack of classical backreaction by eliminating its kinetic element. The QED process is initiated by the laser beam model's classical external gauge potential Aμ. This is especially evident in the partition function. As a result, Feynman's guidelines are as follows. Use standard wavy lines to describe the quantum field a, which itself is made up of non-laser (probe) light [3]. Dotted lines are often not visible, nonetheless, they assist in dressing up fermions, which are denoted by dual lines, with the Volkov solution. The sketch of the mechanisms is illustrated in the Fig. 1.

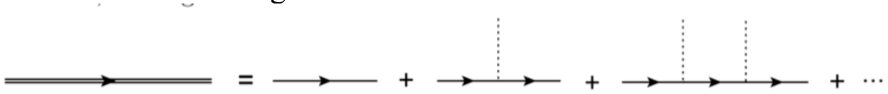

Figure 1. Expansion of a dressed fermion line in terms of bare ones.

Those fermion lines could be outside (asymptotic Volkov states) or inside (Volkov propagator). Subsequently, one can build Feynman diagrams that show the "basic" processes of laser QED with "lego set" of particle lines. During Anton Ilderton's lecture, the about nonlinear Compton scattering, photon-induced, and trident pair formation processes are detailly demonstrated [3] As a result, one ought to focus on fermion loop diagrams that show multiple kinds of vacuum polarization processes, which is schematically shown in Fig. 2.

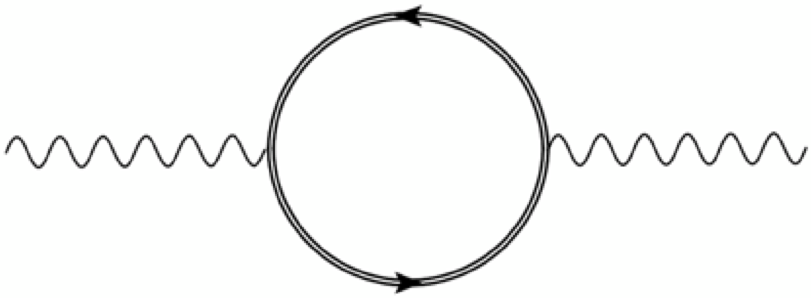

Figure 2. A SFQED vacuum polarization sketch of two gamma photons external to the system.

3. Simulations

Relativistic electrons that are confined by quasistatic circumferential fields may resonate with the pulse and obtain a lot of energy from it. Ion-channel lasers are used in the opposite way to this method [4]. An important condition must be met to speed up electron beams this way, i.e., the oscillation frequency of electrons and phase of the acceleration should always match in an electron comoving frame, which is also called resonance. While it's true that when linearly polarized (LP) laser pulses are used, the process before acceleration needed to achieve resonance behaviour isn't predictable. Only a few electrons are accelerated by betatron radiation, limiting the density and number of energetic electrons and rendering the approach worthless. All resonance electrons move in the same way dynamically, which can be attributed to the SMRA model. This SMRA regime, which permits the development of a collimated relativistic electron beam with a plateau profile, may have important applications in x-ray generation and ion acceleration [4]. Based on utilizing techniques to deduce the pre-pulse (e.g., plasma mirror_ and an extremely ultra-short pulse with an amplitude of 3×10^{23}W/cm^2, one is able to create dazzling -ray emission and dense GeV pairs, as well as high harmonic generation. After traveling dozens of microns through a reasonably dense plasma, the laser is reflected and fragmented into little wave packets by the solid surface. The distorted oscillating mirror's focusing and compression actions boost the mirrored precise mathematical harmonic field's intensity. While clashing with the reflected attosecond pulses, the radiation trapped electrons release -photons [5].

Configuration of the simulation: The linearly polarized laser pulse propagates in the x-direction. It is intensely concentrated on the target of 3×10^{23}W/cm^2. The pulse has Gaussian temporal profile with length equal to 15 fs of the field's peak (duration), and Gaussian distribution in the transverse direction $a = a_0\exp(-r^2/\sigma^2)$.

According to the simulations, the density of trapped electrons varies in proportion to the scale length of the laser intensity profile (the black curve). At $33T_0$, Figure 3a shows the energy of electron and angular distribution. The radius is scaled by the electrons' energy, normalized to GeV. The accelerated electrons mostly propagate forward with a modest opening angle, copropagating with the laser beam. As a result of the small χ_e, the ray emission is inhibited at this stage. As can be observed in Fig. 3b, the amount and energy of photons that are generated are negligible. It looks like electron beam synchrotron radiation at this point, as predicted in Ref. [4, 6], where forward radiation is dominated by resonant electrons accelerated in the plasma channel immediately by the laser beam [5].

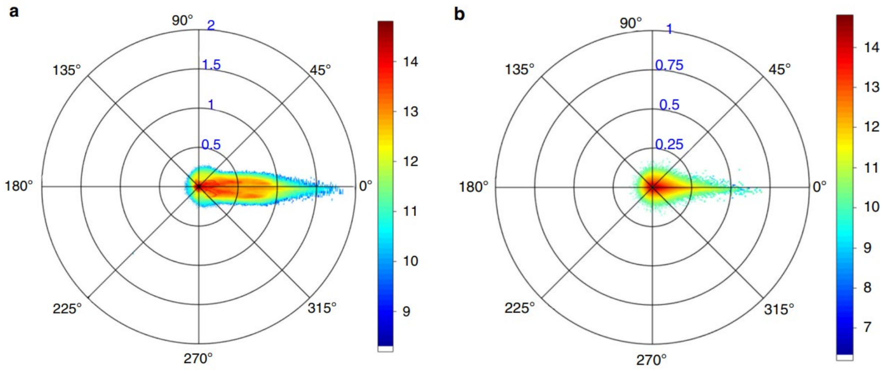

Figure 3. Early electron and photon at $33T_0$. Frames a and b show the energy distribution of two particles [5].

4. Application

Utilizing a Monte Carlo method and coupling it to a particle-in-cell (PIC) algorithm to allow self-consistent quantum electrodynamics plasma simulations. To date, the development of a relativistic thermionic-positron plasma in the experiment has remained an ambitious research aim. Due to the mass symmetry of plasma components, electron-positron pair plasmons are theoretically fascinating. One remarks that processes that are not included in the model may be significant under certain circumstances. When the pair production rate is modest, for example, the second-order trident process dominates.

Additionally, to the Coulomb collisions between positive and negative ion in the plasma, extra collisional events may occur. Photons from gamma rays, for instance, photons from gamma rays and electrons/positive numbers (Compton scattering).

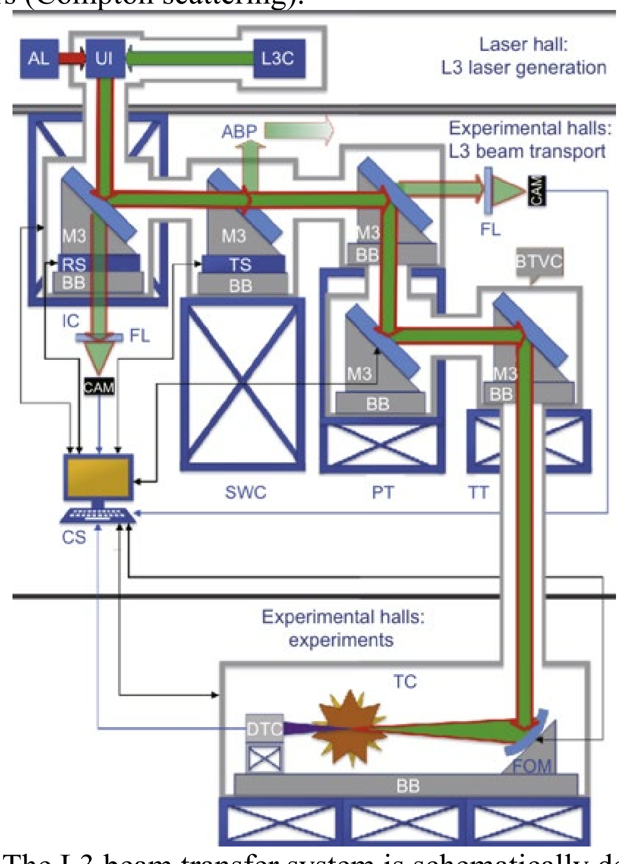

Figure 4. The L3 beam transfer system is schematically depicted [7].

One of the three pillars of efforts to develop an extreme light infrastructure, Eli-Beamlines (Eli-BL), will be perfectly positioned to perform research in HEDP (represent High Enegy Density

Physics), Plasma Physics, and Ultra High Intensity (> 10^{22}W/cm^2) laser-plasma contact. The ELI-BL laser (10 PW) allows researchers to investigate a variety of topics, from high-field physics to new radical states of matter [7]. The L3 beam of ELI is schematically illustrated in Fig. 4.

In Fig. 5, with each pulse of the laser, a high-intensity beam of photons is ejected into the plasma. The duration and width of this burst are related to the plasma's wavelength. The laser's radiation pressure pushes plasma electrons out from the laser's path. Plasma ions pull them back toward the laser path. The laser pulse generates a relativistic electro plasma wave, and at the bubble's end, electrons self-inject and accelerate. The amplitudes of the µm plasma fields created in LPA are not constrained by DC breakdown. In approach, plasma acceleration may generate a gradient of bright and energetic electrons a thousand times greater than conventional accelerators. Researchers stated in 2004 that they were able to generate MeV, pC electron beams with quasi-monoenergetic spectra and milliradian divergence. As a result, LPA has the potential to develop into a new class of tiny electron sources capable of producing beams suitable for synchrotron radiation uses.

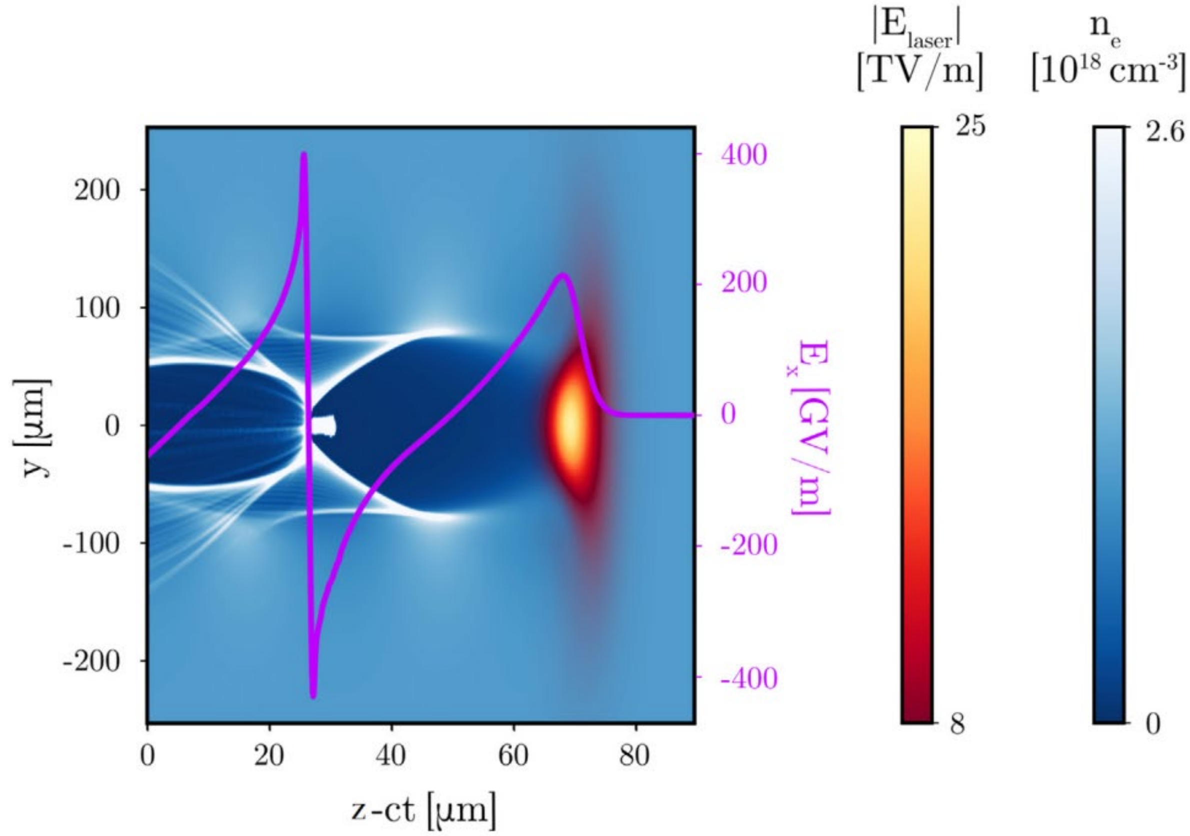

Figure 5. A powerful laser pulse moves in the direction of positive x through a plasma that was not very dense (the red–yellow colorbar depicts its electric field). A relativistic plasma wave is formed after the laser (The plasma electron density represented in blue bar). An electron bubble forms as a result of the laser (On the transmission axis, the associated lengthwise electric field is shown in purple). Negative electric field at the bubble's edge may be exploited to generate an accelerating cavity for moving electrons. The bubble's edge is pumped by an electron beam [8].

5. Limitation & Future prospect

As a matter of fact, contemporary studies have some limitations and drawbacks. Laser peak power has increased dramatically since chirped pulse amplification was introduced. It has already reached 2PW, and 10 PW projects in various nations are in full flow. The lack of experimental aspects is inevitable, but once the peak laser intensity of the predicted energy level is reached by this "time-for-space" method. Academia then needs to adapt the models simulated by PIC and MC. In addition, some spin effects are rarely mentioned in the model. In 2007, the Shanghai Institute of Optics and

Mechanics obtained a laser output of 0.89PW, and then quickly reached 2PW, 5 PW, and 10PW. What is even more exciting is that the Shanghai Institute of Optics and Mechanics recently announced the development of a 100 PW ultra-high peak power laser system, which has attracted the attention of countless scientific researchers [9-11].

6. Conclusions

In summary, this paper discusses the recent progress of EP pairs and Gamma ray produce in Ultra intensity laser and introduce the state-of-art applications with PIC. According to the analysis, the SMRA model takes into account the fact of resonance, which is in agreements the analytical prediction. When LP is used, the pre-acceleration necessary to establish resonant behavior is essentially random, with only a few electrons experiencing conflict of betatron resonance acceleration. Besides, the way to calculate the yields of laser intense and target geometric and to predict the likelihood of plasma formation with PIC are also demonstrated. In the future, the construction of a larger energy level laser can better modify the model and solve the appearance of some unexpected parameters. Overall, these results offer a guideline for further exploration of laser plasma interaction in the QED regime.

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