

The laser matter interaction in the QED regime

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Abstract. Contemporarily, with the rapid development of the laser techniques, the peak intensity of the laser reaches 10^{23} W/cm². In this case, the laser plasma interaction enters the QED regime. With this in mind, this research demonstrates the state-of-art simulations results in the frame. Specifically, a brief introduction to the QED effect is introduced primarily. Subsequent, the progress of ultra-intensity laser, and the state-of-art facilities are discussed. Afterwards, the theoretical description of Compton scattering and Electron-Positron pairs generation are discussed. Eventually, application of high intensity gamma ray and EP pairs are presented. These results shed light on guiding further exploration of the QED physics.

Keywords: strong field QED, ultra-intensity laser, laser-plasma interaction.

1. Introduction

The QED theory depicts the fundamental particles like electron or photon interact with each other. Due to its wide application, it can predict an experiment up to 12 significant figures [1]. QED was established by Dirac when he put forward the relativistic form of Schrodinger equation in 1930s. It was completed by Feynman, Tonanaga and Schwinger in the 1950s. The field created by a single photon is very weak. Therefore, the results can be well approximated by perturbation theory. Naturally, one wants to figure out what will happen if the external field is very strong, which means a field created by a beam of photons or a group of photons. The field generated by laser obviously meets this requirement. The parameter reflecting intensity of laser field is η_e .

$$\eta_e = \frac{|e|a}{m} \quad (1)$$

There are other nonperturbative phenomena, e.g., the Schwinger effect [2], electron positron pair generation [3]. In astrophysics, the way matter interacts with each other in those fields is a very important issue [4, 5].

The motivation of this paper is to probe the QED effect in an extreme condition with laser matter, and raise fundamental questions for quantum mechanics and astrophysics. To be specific, the current progress in the laser techniques and the QED exploration scenario will be discussed. The rest part of the paper is organized as follows. The Sec. 2 will introduce the recent progress of the laser techniques, especially after the invention of CPA techniques. The Sec. 3 will present the analytical description of QED processes. The Sec. IV will demonstrate the state-of-art applications and the Sec. V will discuss the current limitations and offer a future outlook. Eventually, a brief summary is given in the last section.

2. Progress of ultra-intensity laser

Contemporarily, with the rapid development of the laser techniques, it is feasible to use laser pulses to probe physics in QED region. Because the laser contains many photons in every pulse, it allows to treat the laser field as a fixed, classical field. Therefore, laser becomes a very important tool to study new QED effect under such a background field. The strength of laser was characterized by the parameter:

$$a_0 = \frac{e\lambda E}{mc^2} \quad (2)$$

Here, a_0 is the ratio of energy obtained by the electron when you hit the electron with laser. If a_0 is greater than 1, the electron was accelerating to a very high speed, which can cause a strong relativistic effect [6]. Currently, the optical laser systems can achieve $a_0 > 1$, and in this case one cannot use perturbation theory to calculate the result.

The strength of the laser can cause vacuum instability, and that's why we are interested in creating high intensity laser [7]. One can increase the energy density in every pulse to get a high intensity laser or also decrease the focal spot radius to obtain higher energy density. The most economical and efficient way to obtain a high intensity pulse was to make the pulse as short as possible, which seems to be an unattainable object at that time. In 1985, the solution was offered with the invention and demonstration of the concept of Chirped Pulse Amplification (CPA) [8]. The mechanics of this machine is to use the large amount of Fourier frequencies forming the ultrashort pulse. A few years after CPA was invented, the conventional laser amplifier was replaced by OPA (optical parametric processes), which brings the energy of laser pulse to a new level. Nowadays, the highest intensity laser planned can provide intensities $\approx 10^{23} W/cm^2$.

3. QED effect for intense laser

3.1 Compton scattering

One of the most famous experiments that showed laser QED effect is Compton scattering. The experimental setup is following. One uses an X-ray of frequency ν_0 and corresponding wavelength λ_0 to hit a graphite target and we would observe emitted electrons making an angle ϕ to the horizontal and radiation making an angle θ to the horizontal with wavelength λ_1 corresponding frequency ν_1 . The results are quite unexpected. One measured the emitted radiation which supposed to be the same wavelength and frequency with the original X-ray. According to the results, it is found that except the radiation with the original wavelength of λ_0 , there are radiation with wavelength λ_1 greater than λ_0 . Besides, the wavelength difference is proportional to the angle ϕ :

$$\Delta\lambda = 2 \times 0.0241 \sin^2 \frac{\phi}{2} (A) \quad (3)$$

The theoretical explanation is to use two conservation laws:

$$\begin{cases} h\nu_0 + m_0c^2 = h\nu + mc^2 \\ \frac{h\nu_0}{c} n_0 = \frac{h\nu}{c} n + mv \end{cases} \quad (4)$$

where

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}} \quad (5)$$

By solving these equations, one obtains the result:

$$\Delta\lambda = \frac{h}{m_0c} (1 - \cos \phi) \quad (6)$$

On this basis, it shows that the wavelength difference is independent of the scattering matter, and it is only dependent of the scattering angle ϕ . One can understand this result in this way: the electron was bound in the state of the scattering matter's nucleus, and the bond of those electrons far away from nucleus are weaker than those electrons closed to the nucleus.

Therefore, the process of high frequency X-ray hits the electron can be treated as it hits a free electron. On the other hand, if the X-ray hits the inner electrons, in this case the X-ray is actually hitting the atom. So, the mass in the previous formula will become very larger which corresponding to a very short wavelength difference. When one plots the intensity of the radiation to the wavelength at different values of ϕ , the results are very great.

3.2 Breit-Wheeler Electron-positron generation

Positron is the first antiparticle discovered by human beings. Since it was discovered in 1933, it has been widely used in scientific research, medicine, industry and other fields. The generation of

electron-positron pair beams is a very important research topic among many fundamental fields in physics, and what we are looking forward to achieve is to create a very strong external field which enables us to understand the dynamics and formation of pair plasmas under such a strong field. In the laboratory we are facing a problem that we have to be able to generate the pair plasma with enough density to trigger the collective effects. Ultra-intensity laser can achieve this object, and the results were tested well by many experiments in recent years [10]. When the intensity of the laser is strong enough, it leads to the interaction between light and matter into the mechanism dominated by QED, which triggers high-energy gamma photons Radiation and dense electron positron pair generation. Fig. 1. Illustrates the Feynman diagrams for B-W processes [11, 12]. Originally, the collision of two energetic photons is consisted in the process of Breit-Wheeler Electron-positron generation, and the two photons combined their energies to create electron pair. In the nonperturbative regime, the polarization of the laser field will decide how many pairs can be created.

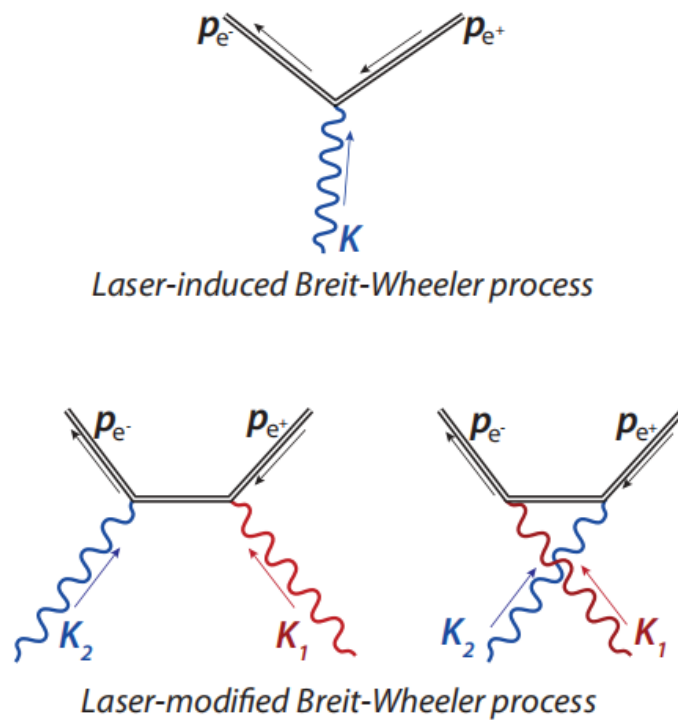


Figure 1. The sketch of the Feynman process of B-W process [12].

4. Application

4.1 High intensity gamma radiation source

High energy radiation source has become an indispensable tool in the fields of basic science, medicine, and industry. The laser QED effect can provide stable and lasting high intensity gamma radiation source. Extreme strong field laser will cause nonlinear QED radiation effect, which can generate high intensity gamma ray. For example, the super intense laser device such as EU extreme optical infrastructure, Shanghai ultra-strong laser device, and France Apollo laser device, etc. High intensity gamma radiation source also plays an important role in scientific research. In 2018, the joint experiment led by imperial college of technology and Queen’s university of Belfast, using the high-energy electron beam to collide with the high intense laser field, and they observed damping effect in the strong electromagnetic field [12, 13]. With the development of science and technology, it is urgent to produce high intensity gamma radiation with shorter pulse width and smaller size [15-17]. For example, in the study of material structure dynamics and chemical reactions, the required time scale is generally femtosecond, so one needs gamma ray with very short pulse to distinguish the vibration and rotation of the molecule.

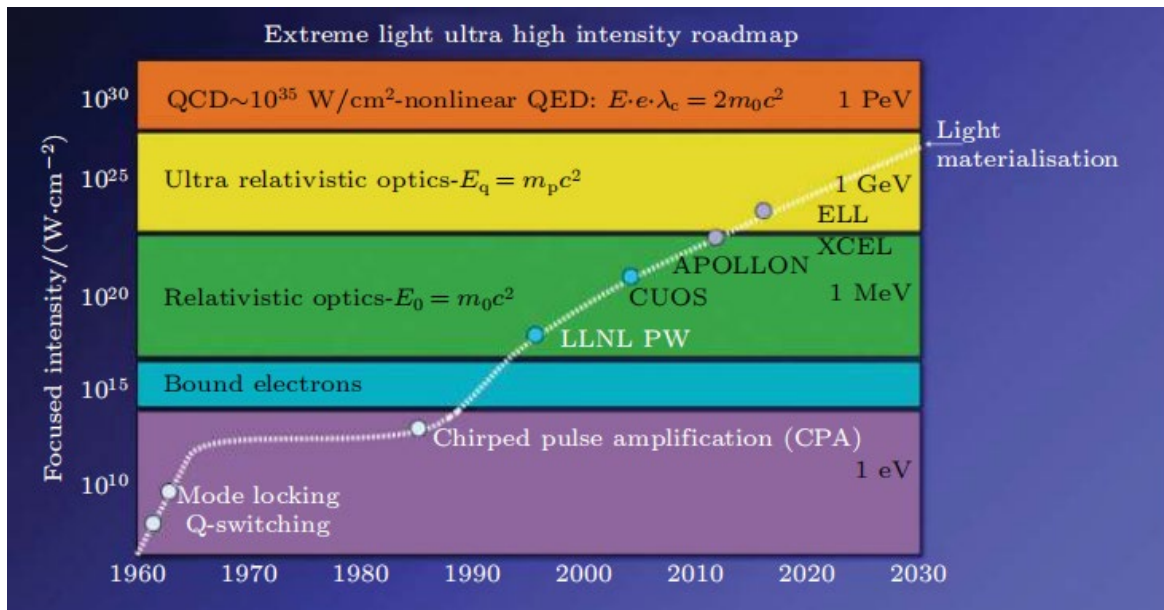


Figure 2. Progress of the focused laser intensity over years and the development of laser-driven physics [18].

4.2 Imaging technology

As just mentioned above, laser induced QED effect can provide a high intensity gamma radiation source, and one of the most important applications of high intensity gamma ray is imaging technology. Imaging technology is not only the hottest topic in the information industry, but also the high-tech combination with the demand in space technology and other fields. Intuitive image is not only an information carrier that people can remember most easily, but also the most abundant and accurate recording method.

In the imaging technology based on radiation and spectrum, high intensity gamma ray can enhance radiation resolution which allows people to know some very tiny structure, e.g., DNA fragments. Polarization is a part of radiation resolution. By using the polarization intensity value, degree of polarization, angle of polarization, polarization ellipticity and emissivity information of target radiation and reflection, it can solve the problem that traditional photometric detection cannot solve [19]. Spectral resolution refers to the minimum wavelength interval that the remote sensor can distinguish when receiving target radiation. The smaller the interval, the higher the resolution. The high intensity gamma ray has a very short wavelength, which can provide a continuous spectral of atoms.

4.3 Large Hadron collider

A very significant application of Electron-positron pairs is to make these two particles collide and produce energy [20]. Plenty of experiments with matter and anti-matter had been done with LHC routinely these days. After the creation of a pair of electron and positron, one puts them on both sides of the collider, then accelerates them and make them annihilate in the middle of the LHC (as illustrated in Fig. 3). Hence, this becomes a very important way to discover new particles. According to the famous equation:

$$E=mc^2 \tag{7}$$

One knows that mass is nothing but a different form of energy. From the creation and annihilation of EP pairs.

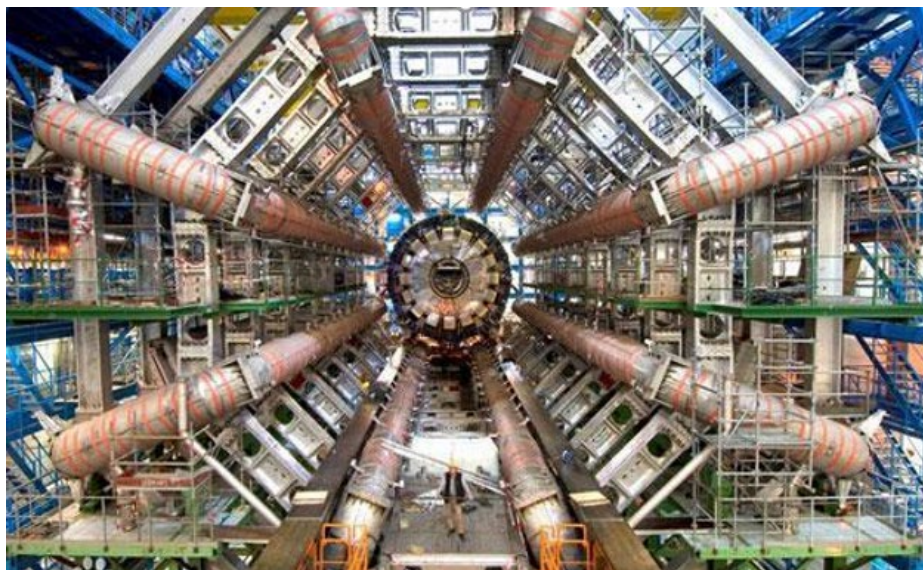


Figure 3. CERN's Large Hadron Collider [20].

4.4 Positron Emission Tomography

Anti-matter like positron is not just for scientific study, but it is being used in hospitals as well. TO be specific, the technology called positron Emission tomography is able to scan location of a cancer. The mechanism of behind it is that when you inject a form of radioactive isotopes into your body which can emits positrons, it will annihilate with the electrons nearby. All one has to do is to detect the gamma ray, which is the energy of light released by the annihilation of the EP pairs. The same method can be applied to detect whether the brains are influenced by cocaine, which is a very efficient way to distinguish a drug abuser.

5. Limitation and future prospect

The laser QED effect has been one of the hottest topics in the past century, and it is still a very useful tool to discover new particles and provides stable gamma ray sources nowadays. Although one can already produce the high-energy gamma ray and EP pairs, and commonly use it in the modern experiment, but it is still very hard to produce a high-density positron beam in the lab. Moreover, if one wants to accelerate anti-particles in LHC, one has to polarize it and control the direction of polarization. To be able to accelerate the heavy anti-matter particle, one has to enhance the performance of the LHC and make the energy source controllable so that the energy of annihilation by particles and anti-particles, a more efficient and clean energy source, will be available to be used by mankind.

High energy and density electron positron pairs may widely exist in the universe, and this EP pairs may come from the Big Bang itself. At the empty part of the universe, there are photons and neutrinos, and one has already detected the gamma ray released by the universe, which is a very good proof to the existence of EP pairs in the universe. These gamma ray may be produced under a very strong QED effect. Hence, in the future, it is very necessary to simulate the environment of the strong QED effect which widely exist in the universe.

In the early universe, there are a huge number of matters anti-matters because of the energy released by the Big Bang. If the matter and anti-matter like EP pairs, are at the same amount of each other, that means we will be ultimately annihilated by anti-matter one day in the future, since the universe is expanding and cooling down in every second. Based on the fact we are still exist, one needs a small difference between matter an anti-matter in numbers so that most of them are annihilated away and the remainder is ourself.

6. Conclusions

In summary, this paper discusses the laser plasma interaction in the QED regime based on ultra-intensity ultra-short laser. Specifically, the recent progress of the ultra-intensity laser is introduced initially. Subsequently, the relevant QED processes including Compton scattering and B-W process are discussed. Afterwards, the state-of-art approaches and current shortcomings are discussed in detail. In the future, with the construction of 100PW-1EW laser facilities, it is feasible to realize investigate QED processes in strong field. Overall, these results offer a guideline for development of laser plasma interaction in the QED regime.

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