Applications of Non-linear Inverse Compton Scattering based on the Laser Plasma Accelerators

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Abstract. The generation of energetic photons in the context of inverse Compton scattering has attracted a great lot of interest from many contemporary scientific fields. Radiobiology, materials physics, and medicine are some of the current fields where inverse Compton scattering is used. In this study, the applications of nonlinear inverse Compton scattering will be demonstrated and illustrated based on laser plasma interaction. This paper introduces and highlights the current advancement in this area, which is a crucial component of quantum physics, as well as the potential uses in the future depending on additional study. Thorough explanations are demonstrated and talked about the uses of inverse Compton scattering. To highlight our thoughts on present developments and potential future advancements in the field, we have extended and expanded on the theme using simulations and experimental data. These results pave a path to generate and shed light on guiding further state-of-art proposals for High flux X/gamma ray generation.

Keywords: Laser Plasma Accelerators; Non-linear Inverse Compton scattering; Gamma ray.

1. Introduction

Compton scattering is a widely investigated nuclear relevant phenomenon in modern physics. Physicist Compton received 1927 Nobel Physics Prize for his findings of X-ray generation based on the effects. In Compton finding, X-ray photon transfers energy to electron through electric scattering if the electron is static, increasing the energy of electron and decreasing the energy of photon. On the contrary, if electron has an initial state of high-speed movement, part of its energy is transferred to photon when the electron encounters the photon, radiating energized photon to the direction of electron's movement. This phenomenon is referred to as the Inverse Compton Scattering. The Inverse Compton Scattering is very common in the universe, and its radiation spectrum can explain certain phenomenon in astronomical physics, including evolution of black hole as well as radiation of the universe, Zeldovich-Sunyaev effect occurs when the electron and photon undergo inverse Compton effect in gas. This effect provides for a method to survey density perturbation of universe that is almost unrelated to the frequency redshift [1]. Moreover, the radiation spectrum of inverse Compton effect can survey plasms state matter with a high temperature and pressure. This is an important surveying technique in inertial nuclear fusion experiment [2]. There were also components with longer wavelength in the scattering spectrum. This scattering phenomenon is called Compton scattering or Compton effect. Compton projects 0.71 angstrom of X-ray onto graphite, and then measures the X-ray intensity scattered by graphite molecules at different angles. When $\varphi=0$, there is only a single frequency light equal to the incident frequency. When $\varphi\neq 0$ (such as 45 °, 90 °, 135 °), two frequencies of scattered light are found.

According to the conservation of energy and momentum, taking into account the relativistic effect, the wavelength offset, namely Compton offset formula:

$$\Delta\lambda = \lambda - \lambda_0 = \left(\frac{2h}{mc}\right) sin^2\left(\frac{\varphi}{2}\right) \tag{1}$$

It can be seen from the above formula that the change of wavelength depends on φ, and λ_0 is independent. In this case, for a certain angle, the absolute value of the wavelength change is certain. The smaller the wavelength of the incident ray, the greater the relative value of the wavelength change. Therefore, Compton effect γ X-rays are more prominent than X-rays. History is just like this. As early as 1904, British physicist Eve was studying γ The first sign of Compton effect is found in the absorption and scattering properties of X-ray. Radium tube emitting γ Rays, scattered by scatterers, are projected to the electrometer. Insert an absorber on the way of the incident ray or scattered ray to test its penetration. Later, γ The problem of ray scattering was studied by many people. In 1910, D.C.H. Florance of the United Kingdom obtained a clear conclusion, which proved that the secondary ray after scattering was determined by the scattering angle, independent of the material of the scatterer, and the larger the scattering angle, the greater the absorption coefficient.

Then, with regard to Inverse process of Compton scattering, it is a scattering process in which high-energy electrons collide with low-energy photons to make low-energy photons gain energy. The inverse Compton effect causes the photon to obtain energy and shorten the wavelength. The amplitude of this wavelength change is called the Compton shift. Since the first laser in China was announced in 1961, with the joint efforts of national laser research, teaching, production and user units, China has formed a wide range of laser science and technology fields and made great progress in industrialization, which has won a place for China in international science and technology. Recently, Chinese scientists have made new breakthroughs in the laser field. A team from Wuhan recently demonstrated a laser technology that can "write Chinese characters" in the air. So far, lasers have been used to create a series of optical illusions, but before that, they needed dust or clouds as a medium. The researchers behind the new device said that by using ultrashort laser pulses to strip electrons from air molecules and convert them into light, it can draw patterns anywhere. To "illuminate" the air, the laser needs to achieve an energy density of 100 TW per square centimeter, which poses challenges to many other similar laser emitters. However, researchers believe that there is still room for improvement in this technology. More accurate control of laser pulse distribution will enable them to create brighter and larger full-color images in the air.

With the rapid development of ultra-intensity laser techniques, the laser-plasma accelerators is achieved, which offers an extremly high electromagnetic field. In this case, under the framework of QED and local constant field approximation, it is feasible to generate energetic photons via non-linear inverse Compton scattering (i.e., the laser field severs as a backround field). The goal of this study is to outline recent findings in this field of study and propose some nonlinear inverse Compton scattering applications based on laser plasma interaction. We will give some fundamental explanations, the background of it, the evolution of laser-related technologies, the current laser intensity that may be achieved, and some simulations. On the basis of inverse Compton scattering, we will discuss some findings from laser plasma interactions (laser electron beam collisions) that result in gamma rays. To illustrate how inverse Compton scattering interacts, we shall offer a Feynman diagram. Next, we will discuss various experiment settings and recent findings. After that, we will go over various nonlinear inverse Compton scattering applications, their drawbacks, and prospects for the future. Finally, the conclusion part will wrap up the essay by summarizing the subject.

2. Basic Concepts

Compton scattering is a process that leads to the photons to lose energy and part of the energy will be transferred to the recoiling electrons. When the electrons transfer its' energy to a photon, it is called inverse Compton scattering. As already mentioned above, Compton scattering is a kind of inelastic scattering, which has different wavelength between the incident and reflected light. The experiment made by Compton has reveal that the electron can be treated as free after scattering due to the energy is larger than the ionization threshold [3]. The original experiment devices has shown in the Fig. 1. Later, in the passage from Compton published on the magazine states that the energy of light quanta depends only on the frequency of the light. In aaddition, there is a mathematical relationship in his experiment which coped with his derived relation before. Inverse Compton scattering is an elastic scattering process between photons and free electrons, but the energy is transferred in the opposite direction. Energy is transferred from electrons to photons, and from photons to electrons. Feynman diagram is a graphical method representing the interaction of elementary collision which is widely used to represent the Compton scattering and the inverse scattering [4]. The Fig. 2 is the Feynman diagram which exemplifies the inverse Compton scattering.

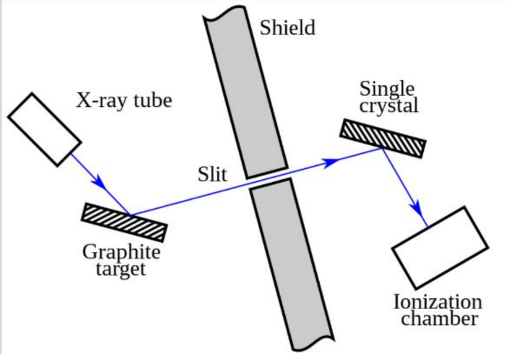

Fig. 1 A schematically diagram for expriment setups for compton scattering.

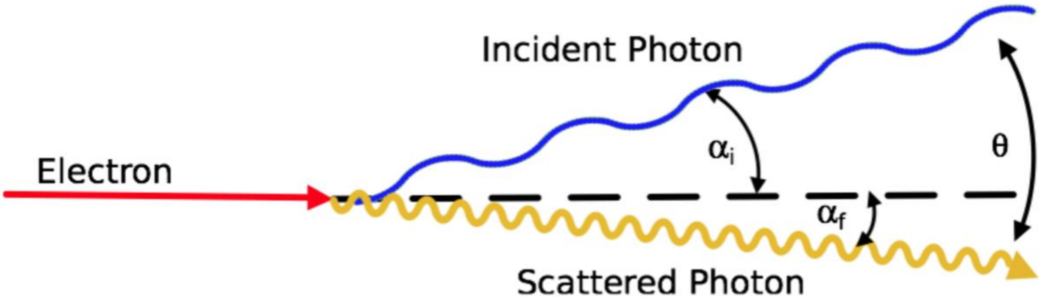

Fig. 2 The Feymann diagram of the process.

It is clearly that the electron with intrinsic angular momentum changes into incident photon and scattered photon after collision. The horizontal axis represents the displacement while the vertical axis represents the time. Moreover, by using the formula, the energy can be defined by the following way. First of all, let's define the energy of photon as $\hbar\omega$ and the angle of the incidence θ. Since $\hbar\omega \ll m_e c^2$, the energy in the frame S'is

$$\hbar\omega' = \gamma\hbar\omega\left[1 + \left(\frac{v}{c}\right)cos\theta\right] \tag{2}$$

with the loss rate

$$-\left(\frac{dE}{dt}\right)' = \sigma c U'rad \tag{3}$$

Then, the result will be

$$U'rad = Urad \int_0^\pi \gamma^2[1 + \left(\frac{v}{c}\right)cos\theta]^2 1/2\, sin\theta d\theta \tag{4}$$

The final form of the loss rate is

$$\frac{dE}{dt} = \frac{4\sigma c Urad\left(\frac{v^2}{c^2}\right)\gamma^2}{3} \tag{5}$$

Moreover, the cross-section of the inverse Compton scattering also plays an important part. The likelihood of Compton scattering per one collaboration with a molecule increments straightly with nuclear number Z, since it relies upon the quantity of electrons, which are accessible for dispersing in the objective particle. The rakish dispersion of photons dissipated from a solitary free electron is portrayed by the Klein-Nishina equation:

$$\frac{d\sigma}{d\Omega} = \frac{1}{2r_0^2(1+\cos^2\theta)\left[1+2\epsilon\sin^2\frac{\theta}{2}\right]^2}\left\{1+\frac{4\epsilon^2\sin^4\frac{\theta}{2}}{[1+\cos^2\theta]\left[1+2\epsilon\sin^2\frac{\theta}{2}\right]}\right\} \tag{6}$$

3. Laser accelerators

For electrons accelerated from laser plasma wake field, they will oscillate horizontal in plasma cavitations as a result of horizontal electric field focusing force and vertical accelerating electric field, producing betatron radiation in the tangential direction. This leads to new ultrafast radiation or particle source due to the interaction between ultrastrong and ultrashort relativistic electron beam in laser wake field and other matter. For example, the collision between electron and scattering laser brings the high-energy X/γ laser source for inverse Compton effect. In addition, the interaction of electron and high Z solid target leads to products including femtosecond collimated positron source and bremsstrahlung. A typical skech is presented in Fig. 3.

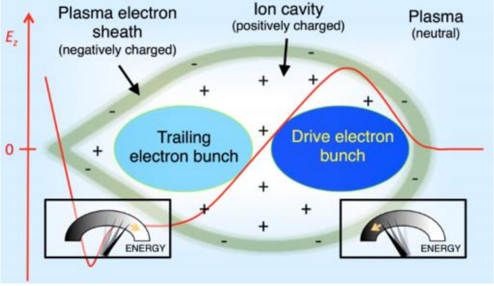

Fig. 3 A sketch of the wakefield acceleration.

When the laser device was just invented, scientists, based on traditional accelerator, proposed and experimentally verified the inverse Compton effect theory that the collision of high energy electron and low energy laser photon produces energized gamma radiation [5]. Currently, the technique of obtaining the source of inverse Compton effect based on traditional accelerator becomes more advanced. In 2018, scholars inluding K. E. Deitrick obtained bright and high throughput compact Inverse Compton effect light source from the collision of superconducting RF cavity accelerating electron and 1 MV laser beam. The obtained average light intensity reaches 3.4×10^{14} phs/(s mm2 mrad2 0.1%BW) [6]. As ultra intense and ultra short laser pulse technology develops, scientists now can harvest high quality relativistic electron beam through methods of laser wake field beam acceleration. It becomes possible to achieve inverse Compton effect through all optical layout. Energized electron moves in laser field and interacts with laser photon, radiated outward inverse Compton laser source. From the perspective of quantum mechanics, it is plausible to distinguish inverse Compton effect into three distinct types based on the number of photon absorbed by a single electron, in other words, the intensity of laser beam. (I). a0 < 1, single photon scattering; (II). a0 ~ 1, low order multiphoton scattering; (III). a0 >> 1, high order multiphoton scattering. These three types of inverse Compton effect is significantly correlated to the photon intensity of scattering light. The higher the photon intensity, the more photons a single electron can absorb at one time, and the more energy that is transformed into high energy photon.

When a0<1, inverse Compton effect is a linear scattering process. The electron absorbs a single photon, and the X/γ laser energy radiated is proportional to the relativity factor of electron and the frequency of fundamental frequency light. Therefore, it is possible to condition the energy of radiation source by manipulating the energy of electron beam. It is worth noting that linear inverse Compton Scattering can use monoenergetic electron beam to obtain laser sources with a great monochromaticity. This is a unique advantage that cannot be replaced by the nonlinear inverse Compton scattering. When a0 ~ 1 or a0 >> 1, inverse Compton scattering is a nonlinear scattering process. The energy of radiated X/γ radiation is proportional to the number of photons absorbed by the single electron. The energy of radiation is related to the number of photon of the electron scattering and the frequency of fundamental frequency wave. The greater the laser intensity, the more control of radiation there is, the greater the acceleration that radiated laser electron has, and the higher the energy that ultrafast applied photons have.

4. Simulations and experiment

Contemporarily, lots of simulation schemes as well as experimental setups have been proposed in order to obtain high beam flux, high quality gamma photons/rays. A typical all-optical scheme to obtain the gamma ray is illustrated in Fig. 4. In this scenario, a laser is utilized to drive the electron beams accelerated via the bubble field [7]. Subsequently, a plasma mirror is adopted to reflect the laser pulse, and the beam is interaction with the electrons, which in turn generated the high energy X/gamma rays via non-linear scattering. Corresponding experiments are carried out which tallies well with the PIC simulations.

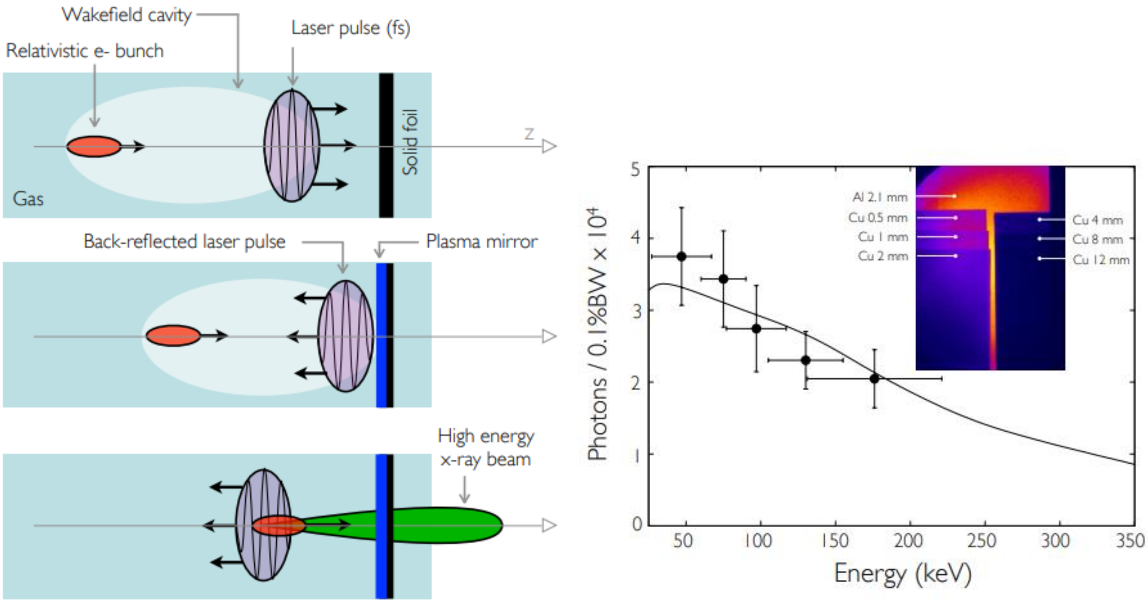

Fig. 4 A sketch of the all-optical scheme for gamma ray generation and energy spectra for experiment.

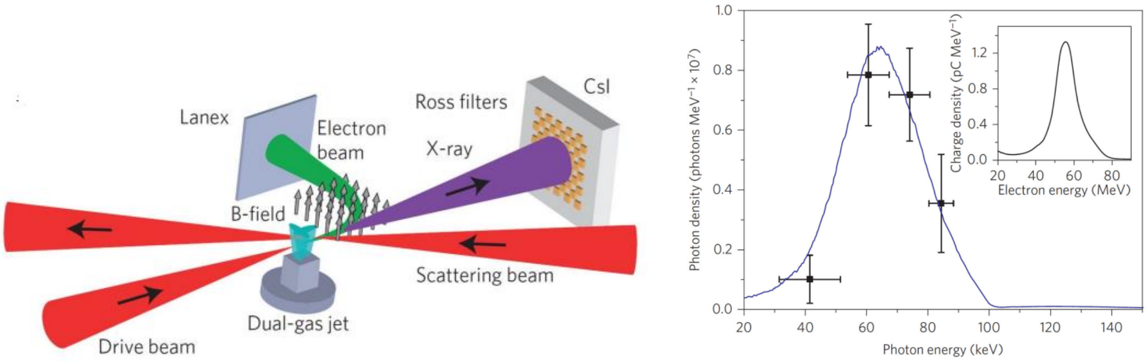

Fig. 5 A sketch of two-pulses scheme for gamma ray generation and energy spectra for experiment.

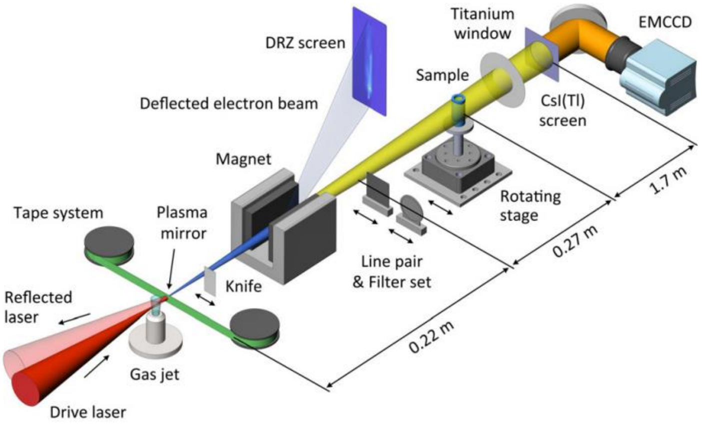

Fig. 6 A sketch of the state-of-art experimental setups.

In addition, other scholars also present other schemes to obtain mono-energetic beam [8]. As shown in Fig. 5, a laser is utilized to drive a wakefield to accelerate the electrons, the other laser serves as the scattering laser, which generates the high energy photons. In this case, the energy spectrum can be controlled. There are other approaches are under investigation [9], e.g., schematically diagram shown in Fig. 6, which is believed to obtain higher photon energy.

5. Applications

With the development of technology, scientists have used inverse Compton Scattering in many aspects. The ICA can create super short and tight transfer speed light heartbeats, tunable from the super bright (EUV) to the γ-beam system, while expecting far lower electron energies than ordinary light sources in view of attractive addition devices. It offers a clever exploration device in a wide scope of essential and applied science. Especially in some area like medical, laboratory. In the meantime, photo-nuclear applications and radiography can be achieved by the inverse Compton scattering. By utilizing backwards Compton dispersing where the attractive field is supplanted by an electromagnetic wave from a laser beat. This interaction requires less work to deliver high energy radiation, yet current sources must be streamlined further to create greater result radiates.

Second, inverse Compton dissipating is significant in astronomy. In X-beam space science, the growth circle encompassing a dark opening is ventured to create a warm range. This is derived to cause the power regulation part in the X-beam spectra (0.2-10 keV) of accumulating dark openings. The impact is likewise seen when photons from the vast microwave foundation (CMB) travel through the hot gas encompassing a system group.

6. Limitation & Prospects

Nuclear physics study and discoveries are being furthered through the application of new technologies and apparatus. Due to its unique equipment, features, and functions, the ELL-NP project is regarded as one of the most state-of-art laser facilities [10]. The ELI-NP facility will make it possible for the first time to conduct quantum electrodynamics (QED) experiments using two 10 PW laser beams. Electrons will be accelerated to relativistic energy by the initial beam. Intense gamma ray radiation and the production of electron-positron pairs are two QED processes that will be applied to relativistic electrons using the second beam. The laser beams will be concentrated to energies greater than 10^{21} Wcm^{-2} and, for the first time, 10^{22}–10^{23} Wcm^{-2}. To increase the intense magnetic and electric fields created by concentrated laser beams. The exploration of novel physical phenomena at the intersections of plasma, nuclear, and particle physics will be made possible by this. Besides, researchers had displayed an unused conceptual plan for an ICS source that's more than two orders of greatness brighter than the Lyncean Compact Light Source (CLS) as of now in client operation. It will permit exchanging numerous inquire about, mechanical and therapeutic applications from the synchrotron, where capacity and access are constrained, to a nearby lab or clinic [11]. For better modeling of collisions in kinetic plasma simulations, neural networks can be used. Neural networks can now be used quickly during run-time in OSIRIS simulations. The AI library is currently being optimized by more effort. focuses especially on utilizing the matrix multiplication parallelization in HPC systems. There is a lot of research being done in this area, and new methods are being developed to address issues in various branches of science, but there is a lot more to inverse Compton scattering than has yet been discovered. It is anticipated that researchers will explore more aspects of Compton scattering in the future and use these aspects to advance this area of study.

7. Conclusion

In summary, this paper discusses the generation and application of high energy photons via inverse Compton scattering based on laser-plasma accelerators. To be specific, the basic principles of the Compton scattering are introduced, and the concepts of the laser plasma accelerators are demonstrated. Afterwards, the PIC simulations result as well as the experiment results are discussed and the possible applications in terms of the high energy photons are also clarified. Nevertheless, it should be noted that the repetition and stability of the schemes are not guaranteed ascribed to the variation features of the laser and the stochastic features for QED process. In the future, with the better controlling process of the, it is feasible to obtain gamma-ray with high quality following the scheme. Overall, these results offer a guideline for the gamma ray generation based on the state-of-art facilities.

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