Generation and transport of γ-rays in ultra-intense laser-matter interactions

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An increase of the focused intensity of the laser pulse has opened new research areas such as high energy density physics. In the regime where the radiation reaction effect plays an important role, the electron motion in the laser field becomes dissipative. This results in the decrease of the maximum energy of electrons [1]. By paying attention to this energy dissipation, it is proposed that high energy photons can be effectively generated when the laser and plasma parameters are properly chosen, which shows the possibility of high power γ-ray source [2, 3]. In this case, a large portion of laser energy is transported inside the target by the photons generated via the radiation reaction effect. In addition, for the further understanding of laser-matter interaction exploring of the energy transport by the high flux of γ -rays is crucial.

We are now developing the Particle-in-Cell (PIC) code with inclusion of the interactions of high energy photons and matters, such as the energy relaxation by Compton scattering, the electron-positron pair creation by Bethe-Heitler process and the nucleon production by the photo-nuclear reactions. These processes are calculated in particle transport code such as PHITS [4] and GEANT4 [5], which are widely used in nuclear physics. In ultra-intense laser-matter interactions, however, the generation processes of γ -rays and collective motions of plasmas as well as the γ -ray transport are supposed to be treated consistently. Then, in this paper, we modelled the above photon transport inside of the material for Particle-in-Cell (PIC) codes which treat the plasma dynamics and their interactions with electromagnetic fields self-consistently.

Here, we consider the laser-plasma interaction in the regime where a quantum effect in the radiation reaction is weak, *i.e.*, $\chi_e = e\hbar\sqrt{(F_{\mu\nu}p^{\nu})^2}/mcE_S \sim \gamma_e E/E_S << 1$, where, e,m,c and $\hbar$ are the electron mass, the electric charge, the speed of light, and the Planck's constant, respectively, $F_{\mu\nu}$ and p_{μ} are the field tensor and four-momentum, E is the laser electric field and $E_s \sim 1.3\times10^{18}$ V/m is the Schwinger field. The radiation reaction effect is calculated using Landau-Lifshitz equation [6]. The energy spectrum of radiation is evaluated by using classical form of synchrotron radiation formula for a single electron;

$$\frac{dI}{d\omega} \cong 2\sqrt{3}\frac{e^2}{c}\gamma\frac{\omega}{\omega_c}\int_{2\omega/\omega_c}^{\infty} K_{5/3}(x)dx \text{ , (1)}$$

where $\omega_c = 3\gamma^3 c/\rho$ and $K_{5/3}(x)$ is the modifield Bessel function. By summing up the contribution from the electrons which are decelerated by the radiation reaction, we can obtain the energy spectrum of radiated photons via radiation reaction. In Fig. 1, the radiation spectrum via radiaion reaction calculated by the PIC code is plotted as a red dotted line, where the laser pulse having the normalized amplitude of a=150, a power of 10 PW, and duration of 30 fs irradiates on a solid carbon target attached with preplasma having scale length of L=2.5 μm. We then introduce macro-particles of photons in oder to reproduce the above spectrum by the ensemble of the introduced photons. The photon emission of the energy below $E \leq 10$ keV is not included, since we are interested in the physics related to photons in the γ -ray regime. Then the photon energy is determined by randomly samling from the synchrotron radiation profile where the probability is proportional to the spectrum intensity. The weight of the macro-particle is determined from the energy conservation. In this manner, photons are generated in each time step of calculations when the electrons loose their energies by radiation reaction. The energy spectrum calcluated from the photon macro-particle is plotted in Fig.1 as the black line . The spectrum of the photon macro-particle well reproduces the spectrum evaluated by synchrotron formula (more detail in ref. [7]).

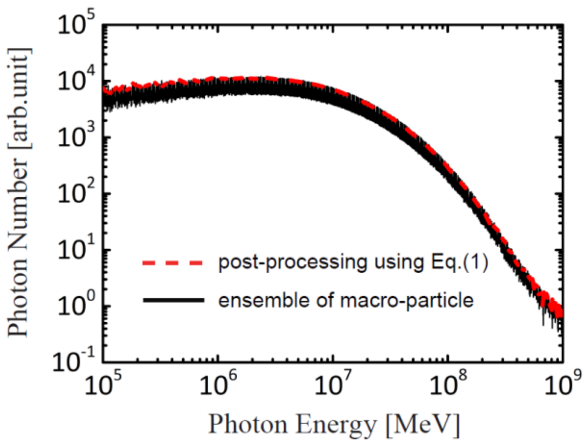

Figure 1. Comparison of energy spectrum evaluated by synchrotron radiation formula as post-processing (dotted-line), and ensemble of the macro-particle of γ -rays introduced in PIC (solid line).

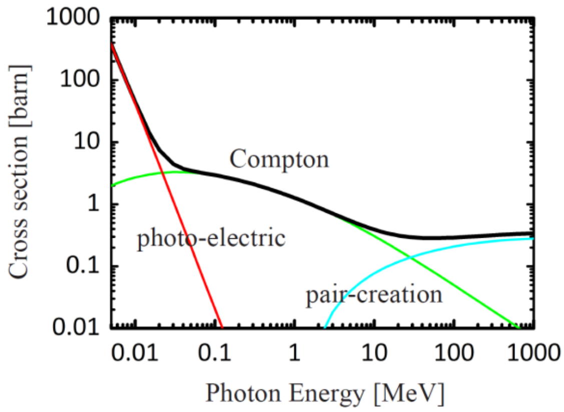

Fig.2 Photo-cross-section for a carbon atom.

When photons propagate through targets, thye interact with atoms and nuclei, which leads to the scattering and abosrption of the photons, and the generations of charged particles and nucleons. Fig. 2 show the photo-cross-section for a carbon target. For photons with energies higher than 10 keV, the cross-section is dominated by that of Compton scattering, where a photon collides with a bound electron and some portion of energy is transferred to the electron becoming a free electron. For photons with energies beyond tens of MeV, electron-positron pairs are created under the electric fields of nuclei. And also photo-nuclear reaction such as (γ,p), (γ,n),(γ,2n), and (γ,α) takes place. These processes are modelled in our PIC simulation code as a Monte Carlo manner. The modelling of photon-matter interactions in our PIC code is verified using a particle transport code PHITS [4]. The detail of the modelling of photo-interactions in our PIC code is explained in ref. [7].

Using the developed code, we can investigate the detail of characteristics generated by the γ -rays transport in targets. Fig. 3 shows the the energy spectrum of the positrons generated by the γ -rays transport, where the simulation conditions are the same as the above.

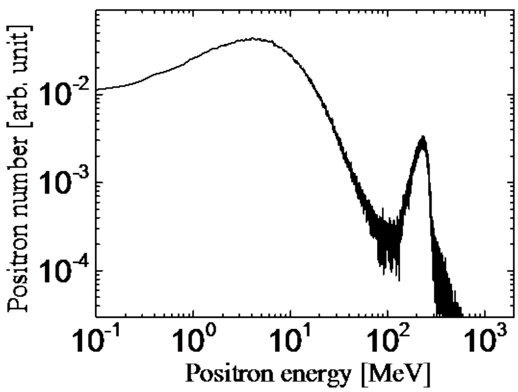

Fig. 3 Energy spectrum of positrons generated by the transport of γ-rays in tergets.

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