A SIMULATION FOR THE OPTIMIZATION OF BREMSSTRAHLUNG RADIATION FOR NUCLEAR APPLICATIONS USING LASER ACCELERATED ELECTRON BEAM

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Abstract

Laser accelerated electron beam can be a compact source for high energetic photon generation for nuclear application. A simulation code using GEANT4 has been developed for the estimation of Bremsstrahlung radiation from laser accelerated electron beams impinging on a metal target and the photonuclear reaction of a sample target.

The energy and angular distribution of Bremsstrahlung radiation depending on different target thickness and electron parameters as well as the emission spectrum due to radioactive decay from the sample activated by high energy photons generated can give us an idea of optimal condition for the desired nuclear applications. We discussed the critical issues of high energy photon generation for photonuclear reaction experiments.

INTRODUCTION

LASER-DRIVEN acceleration of electrons in plasmas was first proposed by Tajima and Dawson [1] in 1979. Tabletop laser systems based on the chirped-pulse-amplification (CPA) technique [2], with pulse duration of tens of femtoseconds and focal spot of several μm for intensities greater than 10^{18} W/cm^2, have made laser-acceleration experiments possible over a wide range of laser and plasma parameters [3]. A breakthrough from several groups successfully demonstrating monoenergetic and highly collimated electron beams with energies of hundreds of MeV [4,5] reported that the increase of the energy gain, reduction of the $\Delta E/E$, and enhancement of the charge of laser-accelerated electron beam is feasible with a precise control of the interaction condition between ultrashort laser pulses and underdense plasmas [6].

Merits of laser-accelerated electron sources, such as, compactness and high peak current, incite us to apply to many fields. Easy accessibility combined with compact local shielding may be especially attracted to a variety of users in small-scaled laboratories in future.

The energies between 10 MeV and 50 MeV of electrons and photons are of concern for nuclear applications related to giant dipole process. A detailed calculation is necessary to estimate the capability of observation in each process and to optimize experimental conditions, since laser-accelerated electron beams have large energy spread and divergence compared to those accelerated by conventional accelerators.

Experiments of laser-acceleration of electrons have been conveyed by using a 10TW Ti:sapphire laser developed at the Korea Atomic Energy Research Institute (KAERI). The laser pulse can deliver up to 300mJ of energy with a pulse width of 30 fs at a central wavelength of 0.8 μm.[7] A helium supersonic gas using 1 mm diameter nozzle is used to produce the underdense plasma, which is monitored and analyzed by using both a bi-prism interferometer and Thomson scattering measuring system.

Electrons with energies of tens of MeV can generate high energy photons via Bremsstrahlung interaction with high Z metal target. High energy photons can induce the photonuclear reactions with matter followed by the radioactive decay.

We have developed a simulation code using GEANT4 toolkit to calculate the angular spectral distribution of Bremsstrahlung radiation from a high Z metal target and to estimate the photonuclear reaction process of the samples (e.g., Au, Cu) due to Bremsstrahlung radiation obtained the above by calculating their radioactive decay line spectrum. The thickness of a converter and the energy of an electron beam required for this experiment are analyzed.

In SIMULATION SETUP, Geant4 classes, experimental geometry, and initial parameters are described. The spectra of Bremsstrahlung radiation and the radioactive decay are reported in SIMULATION RESULTS. In CONCLUSION, we briefly discuss our results and future works for upgrade in simulation.

SIMULATION SETUP

Monte Carlo simulation toolkit named GEANT4 (GEometry ANd Tracking) was developed by many users via international collaboration [8,9], which is for the simulation of the passage of particles through matter written in C++ language [10]. The range of applications includes high energy particle physics, nuclear and accelerator physics, as well as studies in medical and space science [10].

Three main classes for simulations are the detector construction, the physics list, and the primary generator action. User-action classes are also required to access the information of interest. Three mandatory classes and simulation setup are described as follows.

Detector Construction Class

The Geometrical setup includes a converter for Bremsstrahlung radiation, a magnet, for deflecting transmitted electrons, a collimator, a sample for photonuclear reaction, and four monitors for the particle data collection which are the components of the detector construction class. They are positioned in the vacuum space named world volume in GEANT4.

We assume that an electron beam travels in the +z direction. The converter, which is a tantalum disk of 1 cm in diameter and with adjustable thickness, is positioned at z = 0 perpendicular to electron propagation. The bending magnet is placed at z = 3 cm to prevent transmitted electrons from entering into the collimator. The field strength in the gap of 5 mm high and 50 mm long is 0.5 Tesla. It can avoid the contribution due to additional Bremsstrahlung radiation generated by transmitted electrons in the collimator or sample itself

The lead cylindrical collimator is located at 10 cm away from the converter, with a diameter of 5 mm and a length of 5 cm. We can change its radius and length and place it at different angle with respect to +z direction. The sample for activation is placed at the end of collimator. The schematic of simulation setup is illustrated in Fig. 1.

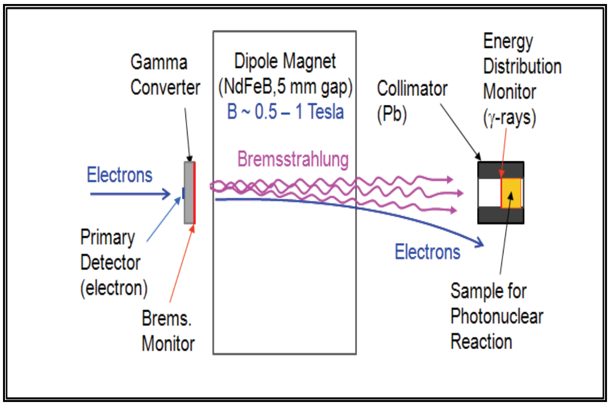

Figure 1: The Schematic diagram of geometrical set-up and monitors for data collecting

Sensitive detector class is used to collect the physical data produced by interactions of particles with any materials and/or at the boundary of geometry [11]. Two monitors on both sides of Ta converter are for calculating the conversion efficiency of Bremsstrahlung radiation over 2π: the front one collects the information of incident electron beam, while the rear, that of Bremsstrahlung radiation. Third monitor in front of the sample measures the energy distribution of high energy photons passing through the collimator. The sample is surrounded by fourth monitor to detect the decay spectrum after activation of sample by high energy photons.

Physics List Class

Physics processes which handle the interactions between particles and matter are defined by the Physics list classes, for example, G4EmStandardPhysics, PhotonInelastic, and G4Radioactive Decay Physics in our simulation. G4EmstandardPhysics includes Photoelectric effect, Compton scattering, pair production, multiple scattering, Bremsstrahlung, ionization, and positron annihilation. PhotonInelastic process in hadronic physics package is used to describe the photonuclear reaction. Radioactive decay physics deals the decay process, such as, species, energies, half-life time of activated nucleus, and so on, combined with GEANT4 data base [12] for radioactive decay processes.

In Physics list class, we can set threshold energy of particle creation either by the energy value or by the length value related to the penetration depth of particle through the matter. In our simulation, we set the length value as a threshold so that only particles with energies greater than 0.99 keV can be created. Usage of length value is better in the system comprising of various materials. Electron, positron, photons (gamma-rays), ion, and neutron are included in this simulation.

Primary Generator Action Class

We generate the primary events using General Particle Source (GPS). GPS allows us to specify the distribution of the primary particle source [13]. The parameters of primary beam can be easily set by using a simple macro file. The peak energy, energy spread, propagation direction, initial position, and total number of electron beam can be selected for a Gaussian electron beam.

SIMULATION RESULTS

The computer system for GEANT4 simulation is made up of Intel Quard-core 2.66 GHz CPU and 12 GB DDR3 RAM and OS is Ubuntu 9.04 server version. It took about 3~4 hour to simulate with 10^7 primary particles. We can get all information we needed, such as, the energy distribution of primary electron beam, the conversion efficiency, spectrum of Bremsstrahlung radiation before and after the collimator, the radioactive decay spectrum, and so on.

We have changed the peak energy and energy spread of incident electron beam, the converter thickness, and kind of sample materials to investigate optimum condition for experiments.

Primary Beam Distribution

Primary electron beam impinging into the converter is assumed to have a Gaussian energy distribution, of which the peak energy is varied from 10 MeV to 50 MeV with two different energy spread, 5% and 10% in rms.

Fig 2 shows the energy distribution of Gaussian electron beam with 30 MeV peak energy, 10% energy spread, and 10^7 electrons.

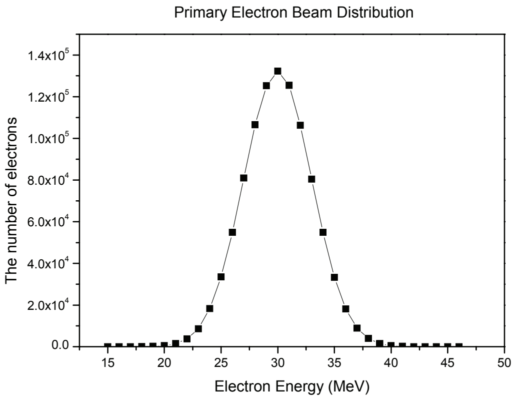

Figure 2: Energy distribution of primary electron beam. (Gaussian, 30 MeV peak energy, 10% energy spread, 10^7 electrons)

Conversion Efficiency with Target Thickness

When the electron energy is between 10 MeV and 50 MeV, Bremsstrahlung is the main process of interaction in matter. Total conversion efficiency typically has the maximum at 0.4 - 0.5 of the electron range at high Z target [14]. However, it is a little bit different when we use the collimator with narrow angle along the beam axis. As the narrower the collecting angle, the thinner the target thickness at maximum conversion efficiency.

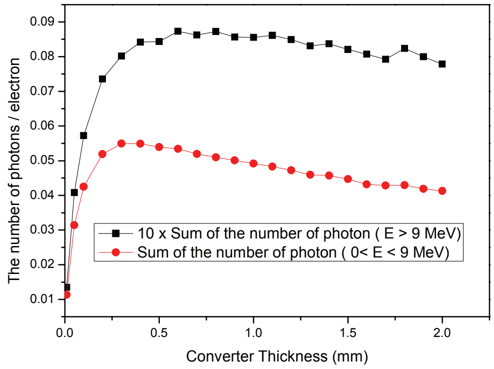

Figure 3: The number of photons collected through 5 mm dia. collimator with respect to the thickness of Ta converter (circle • : the number of photons with energies in 0 < E < 9 MeV; square ▪: the number of photons with energies in E > 9MeV; incident electron beam : Gaussian beam with 30 MeV peak energy and 10% energy spread)

For a thick converter, the angular spectral distribution becomes broader due to multiple scattering effects. To improve the signal to noise ratio, the target thickness should be optimized to have more photons with energies greater than threshold energy (~ 9MeV for Au; 10 MeV for Cu) while minimizing the number of photons with energies below threshold.

We computed the angular energy spectrum of Bremsstrahlung radiation through 5 mm dia. collimator generated by a Gaussian electron beam with the peak energy of 30 MeV and the energy spread of 10 %.

The result in Fig. 3 shows that total number of photons with E > 9 MeV remains nearly constant for Ta thickness greater than 0.5 mm, while that with E < 9 MeV starts to decrease as being increased the target thickness greater than 0.3 mm. Fig. 4 shows that the primary electrons can be easily transmitted through the thinner converter. The transmitted ones will produce the additional noise or the secondary radiations at the collimator. Overall, the result indicates that ~1 mm thick Ta converter is the best choice for given parameters above.

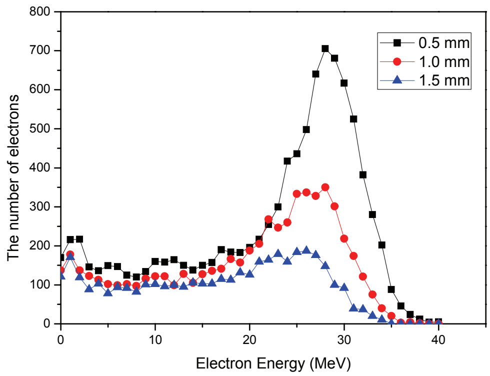

Figure 4: Energy distribution of transmitted electrons at the collimator, with different Ta thickness (30MeV peak energy, 10 % energy spread, 10^6 electrons)

Nuclear reaction probability vs. Electron beam energy

High energetic electrons generate more number and higher energy of photons. Since the photonuclear reaction cross-section for Au sample has the peak around 15 ~ 20 MeV and the threshold near 9 MeV of photons, we need to select optimum energy of primary electron beam with photonuclear reaction cross section.

According to Fig.5, the number of photons involved photonuclear reaction is increased as the electron energy is increased, but its growth rate is decreasing in the energy range greater than 20 MeV. As the energy of electron is increased, the ratio of photons for photonuclear reaction to total incident photon becomes lower and lower. That means the photonuclear reaction efficiency becomes lower with higher energy electron beam. We select the optimized electron energy for photonuclear reaction as 20~30 MeV, which is slightly higher than the electron energy for maximum photonuclear reaction cross-section. It might be slightly changed if we use different size of collimator along the electron beam axis or different position.

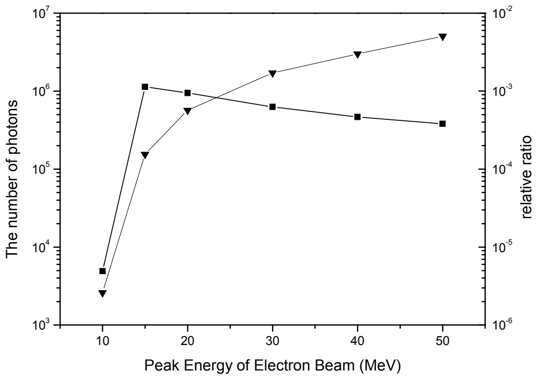

Figure 5: The number of photons inducing the photonuclear reaction (▾) and the ratio of those involved in photonuclear reaction process to total number of photons incident on the sample after the collimator (▪)

Line spectrum of Radioactive decay

Fig. 6 shows the decay line spectrum of Au and Cu samples when primary electron beams with 30 MeV peak energy are used for simulation.

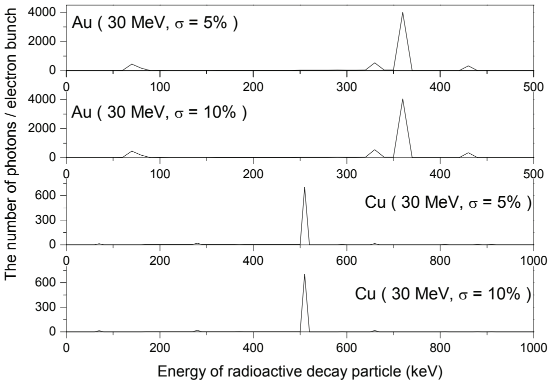

Figure 6: The dependence of the Au and Cu decay line spectrum on the energy spread of electron beam. The number of electrons in a bunch is 10^9.

In the photonuclear reaction, ^{197}Au(γ,n)^{196}Au generates two dominant decay lines at 360keV and 330keV, while 550 keV line is dominant for Cu sample. The changes of their spectra are negligible as increasing the energy spread of primary electron beam from 5% to 10%. Therefore, laser-accelerated electron beams, which typically has 10% of energy spread at 30 MeV, is enough for this experiment.

CONCLUSION

We have developed a simulation code using GEANT4 toolkit to analyze the photonuclear reaction process with a given laser-accelerated electron beam as well as to estimate optimum parameters of electron beam, converter, and collimator, for experiments. For incident electron beam with 30 MeV peak energy and 10% energy spread, the optimum thickness of Ta converter is about 1 mm. The primary electron beam energy of 25 MeV with 10% energy spread is good enough for the photonuclear reaction process in Au or Cu samples. Little dependence of photonuclear reaction process on the energy spread up to 10% of primary electrons tells us that shot-to-shot variation less than 10% of the peak energy of primary electron beam may be insensitive to this experiment. Laser-accelerated electron beam with peak energy of 20 ~ 50 MeV generated at KAERI has both energy spread and shot-to-shot variation much less than 10%.

We are now investigating the background subtracting technique to determine the position and size of a collimator for background spectrum measurement to improve the detection efficiency with broadband gamma rays, like Bremsstrahlung radiation. The upgrade including the response of gamma ray detectors (NaI and HPGe detectors) is also underway. We expect that the upgrade code will give more realistic description for experiments.

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