Gamma-ray generation using a laser-accelerated electron beam

Seong Hee Park, Kitae Lee, Yong-Ho Cha, Young Uk Jeong, Hohyoung Lee, Ji-Young Lee, and Kyung-Nam Kim

A compact gamma-ray source will be more accessible for nuclear applications, including in small laboratories.

Gamma rays are the electromagnetic wave having the highest energy and smallest wavelength. While optical light provides electronic information about atoms, gamma rays analyze the nucleus and nuclear reactions. For example, realizing gamma-ray lasers could make nuclear resonance fluorescence a powerful tool for identifying isotopes in detecting explosives or in analyzing the composition of nuclear materials more precisely. To date, gamma rays generated by a technique called Compton backscattering have proved to be the best quality. They are tunable, quasi-monochromatic, and polarized. However, their accessibility is poor because they require large accelerators. In the decades following the first proposal of laser-induced electron acceleration in 1979, many groups focused on developing millimeter-scale-length accelerators to substitute for conventional kilometer-scale ones. In the 2000s, successful results allowed the scientific community to forge ahead with developing compact laser-induced accelerators as well as compact light sources, such as x-ray free-electron lasers. However, stabilities in energy, pointing, and charge, as well as monochromaticity in energy remain major obstacles.

One of the merits of a compact gamma-ray source using a laser-accelerated electron beam is ease of application. The size of the accelerator is mostly determined by the laser and electron-beam-dump systems. In fact, a laser-acceleration system with electron energy of a few hundred mega-electron volts or less can be installed on two optical tables, fit for small laboratories.

We have developed a 30 terawatt (TW) titanium:sapphire (Ti:sapphire) laser system (see Figure 1) with a laser pulse duration of 27fs after compression and contrast ratio of $10^{-8}$ between the main peak and amplified spontaneous emission of 300ps. The multipass preamplifier gives a high-break contrast ratio compared to a regenerative scheme. We focused laser beams on a helium-gas jet target using an off-axis parabola

![Figure 1. Korea Atomic Energy Research Institute 30 terawatt laser system and characteristics. OAP: Off-axis parabola. FWHM: Full width at half-maximum.](image)

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![Figure 2. The energy spectrum (dI/dE) of laser-accelerated electrons. BM: Bending magnet. TS: Thomson scattering.](image)

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Figure 3. Layouts for gamma-ray generation.

Figure 4. The geometrical set-up and data-collection monitors for simulations using GEANT4 (a toolkit for simulating the passage of particles through matter) and the result of angular energy distribution of Bremsstrahlung radiation: 30MeV, 300pC, 10% energy spread, 2mm-thick tantalum (Ta) converter. NdFeB: Neodymium magnet. Pb: Lead.

(OAP) mirror with a focal length of 272mm. The focal spot size and the Rayleigh range (the distance from the focal point to where the area of the laser beam is twice that at the focal point) may be increased using an iris, but at the expense of laser intensity. With the opening diameter of 40 and 30mm, the focal spot is measured ~7 and ~8.5µm in full width half-maximum, respectively. The electron energy accelerated at a typical range of 20~50MeV, depending on the laser intensity and the dephasing length, which is good enough to generate Bremsstrahlung radiation for photonuclear reactions (see Figure 2). The typical divergence measured was ~10mrad and the energy spread was 10~25%, with incident laser pulses of ~10^19W/cm^2. With a constant intensity at the plasma (~1.3×10^19W/cm^2), the shot-to-shot variation is reduced and the pointing stability is improved, as the larger the laser beam waist, the longer the Rayleigh range. We expect that high-energy electrons of more than 200MeV may be generated to create a few MeV gamma rays via Compton backscattering using a spherical mirror with a 1m focal length and a 2mm-long rectangular nozzle. Figure 3 shows the layouts for gamma-ray generation.

Using a GEANT4 toolkit to simulate the passage of particles through matter,9,10 we calculated the angular spectral energy...
distribution of Bremsstrahlung radiation from a given converter material, the distribution of photons generated and electrons transmitted through the converter at a given geometry (including the bending magnet and collimator), and the photonuclear reaction. The energy distribution of the electron beam after the bending magnet and the collimator is assumed to be Gaussian. The second dipole magnet in Figure 4(a) is for deflecting the transmitted electrons through a tantalum (Ta) converter. Figure 4(b) shows the angular spectral energy distribution of Bremsstrahlung radiation generated by 30MeV electrons with a 2mm-thick Ta converter. The color map with the density in log scale shows that we can select photons with different energy spectrums using a collimator at a certain angle. Thus, we may enhance the measurement accuracy with aids of simulation data (background subtraction), for which a data processing tool is under development. It can also be used to calibrate the total number of photons with energy greater than a certain amount. The measured dose using the survey meter (Bicron RSO-5 ion chamber gauge) can be calibrated to the number of photons per pulse. Using the parameters of the detector (volume, response time, and threshold energy) and calculated color map, the dose rate of 5000mR/h is estimated to $6 \times 10^7$ ph/cm$^2$ of photon energy $>10$MeV at 50cm from the Ta target with the response time of 5$\mu$s.

For the reaction of gold$^{197}$Au($\gamma$,n)$^{196}$Au—the photon yields with different converter thicknesses are calculated at the acceptance angle of $\sim 3^\circ$, which is close to $\gamma^{-1}$ ($\gamma$: Lorentz factor) at 10MeV. For the electron bunch of 300pC at 30MeV peak energy with 10% energy spread, the number of photons with energy $>9$MeV is about $1.5 \times 10^7$ photons per shot in a $3^\circ$ acceptance angle from a 2mm-thick Ta converter. The higher-energy photons ($>9$MeV) are maximized at 0.8mm in this calculation. The effect of electron energy spread on the decay spectrum of $^{196}$Au is negligible. The peak of the 360keV decay line is about 7% higher for a 1mm-thick Ta converter. This is because 10% more higher-energy photons ($>9$MeV) are generated from a 1mm converter than from a 2mm one. And when the peak energy is 30MeV, the 10% energy spread is slightly better for Au activation than the 5% energy spread from higher-energy electrons. But nonetheless, the effect of the electron energy spread is almost negligible. The dependence of the peak energy of electrons should be investigated.

Bremsstrahlung radiation was generated using a 2mm Ta converter to activate the Au sample. The main laser’s pulse energy at 30fs is 650mJ and was focused using an OAP mirror. The gas was ejected at 650psi backing pressure through a 1mm-diameter hole. The laser was injected at 1.35mm, corresponding to an electron density of $\sim 3 \times 10^{19}$. To measure the half-life as a preliminary test, thousands of laser pulses were injected to get enough signal for the decay spectrum measurement. We operated not at the maximum electron energy, but around 25–30MeV to minimize the shot-to-shot variation. The plasma interferogram and Thomson scattering were monitored. Figure 5 shows the decay spectrum of $^{196}$Au and the lifetime of each spectral line of $^{196}$Au, measured by a high-purity germanium detector made by Ortec. The decay spectrum is accumulated every hour, starting one hour after activation. Major decay lines of $^{196}$Au, which is 355.7keV (93.6%), 66.83keV (44%), 333.0keV (24.4%), and 426.0keV (7%), were detected well in agreement with the calculation, except the line near 70keV. The half-decay time measured was 6.188 days.

The clear trace of the laser-accelerated electron beam impinging on the converter showed up on the Ta plate as small dots.
The size and distribution of the dots, which were evidence of the electron beam, corresponded to the divergence of ~10 mrad and the pointing stability deviation of ~3°, respectively. Figure 6 shows the possibility of imaging high-density materials using Bremsstrahlung radiation generated by laser-accelerated electrons.

In direct measurements of gamma rays using a sodium iodide detector (3cm diameter), more higher-energy photons were detected compared to the background, indicating the generation of high-energy gamma rays, but no more details. Even though gating periods synchronized with the laser were adjusted to reduce the continuous background effect, it did not help much due to the intrinsic microsecond-scale response time of the detector. As a result, a measurement system of ultrafast gamma rays should be developed. The simulation estimation based on the measured data is the best one available as an indirect measurement.

We plan to generate Compton gamma rays using a laser-accelerated electron beam and 532nm neodymium-doped yttrium aluminum garnet laser. To increase the flux of gamma rays, we may design a nanosecond-long interaction region or a compton 360° dipole magnet to circulate the electron beam. For long interaction sections, a triplet to guide the electron beam should be used. In the case of a 360° dipole magnet, the emittance growth due to instrabeam scattering in a low-vacuum chamber will be the main challenge.

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