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Feasibility of Strong and Quasi-Monochromatic Gamma-Ray Generation by the Laser Compton Scattering

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1. Introduction

Photonuclear transmutation of long-lived fission products in spent nuclear fuels has been suggested as a potential solution to the long-standing challenges associated with nuclear waste management. One such proposal is to induce the photonuclear reaction using high-brightness gamma (γ)-rays generated from the laser Compton scattering (LCS) interactions [1]. This is because LCS γ-rays are energy-tunable, quasi-monochromatic, and beam-like [2]. The photon intensity of the mono-chromatic LCS gamma-ray should be high or strong for efficient and high transmutation rate. It was recently reported that a so-called energy-recovery linac system is able to produce a very high-intensity LCS photons in the order of approximately 10^{13} photons/s economically [2]. It however did not evaluate quality of the LCS photon beam although a quasi-monoenergetic LCS beam is of huge importance in the photo-nuclear transmutation reactions. It is upon this observation that this paper was prepared. Specifically, this work attempts to quantify intensity of the quasi-monochromatic LCS beam from the said linac system. In addition, this paper aims to discuss general characteristics of the LCS photon, and possible approaches to increase its intensity.

2. The LCS photon

The laser Compton scattering is an elastic scattering of a low energy laser photon with a high energy electron, which results in an increase in energy (smaller wavelength) of the photon, as roughly depicted in Fig. 1 [3,4]. Figure 1 shows the head-on collision between a photon and electron and the angle θ is called the scattering angle of the photon. Note that T and T_s are kinetic energies of incident and scattered electrons, while E_L and E_γ are energies of incident and scattered photons. Further details on the theoretical basis of Compton scattering and related LCS parametric studies are available in Refs. 3 and 4.

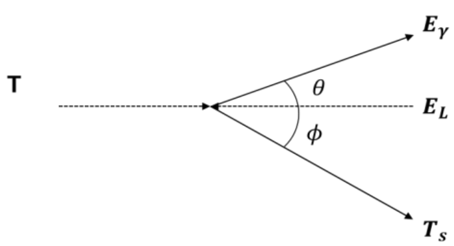

Fig. 1. The laser Compton scattering process [3,4]

Energy of the scattered photon E_γ in the laboratory frame can be calculated from the laws of energy and momentum conservations, and are expressed as a function of laser energy E_L and angle θ:

$$E_\gamma = \frac{(1+\beta)E_L}{1-\beta cos\theta + E_L/mc^2\sqrt{1-\beta^2}(1+cos\theta)}, \quad (1)$$

where β, ratio of electron to light velocities, is

$$\beta = \frac{\sqrt{T(T+2mc^2)}}{T+mc^2} \quad (2)$$

in which *m* is the electron mass and mc^2 is the electron energy at rest. It is clear that the scattering angle should be small enough, i.e., backscattering, for a high energy LCS photon.

2.1 LCS photon energy in terms of scattering angle

Figures 2, 3 and 4 plot energy of the LCS γ-rays as a function of scattering angle for several source laser energies of 0.1 eV, 1 eV, and 10 eV, respectively. Clearly scattered gamma-ray energy in all cases are flat up to certain backscattering angles before decreasing relatively fast. Largest backscattering angle in the flat γ-ray energy domain increases as the electron energy decreases. There is however no apparent relation between largest backscattering angle in the flat γ-ray energy domain with source laser energy. It is important to note that in order to yield high-intensity mono-chromatic LCS photons, the laser energy should be increased and the electron energy should be decreased for a targeted LCS photon energy.

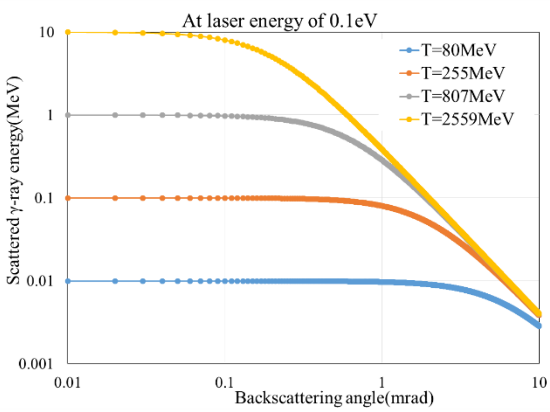

Fig. 2. LCS photon energy as a function of scattering angles at laser energy of 0.1 eV

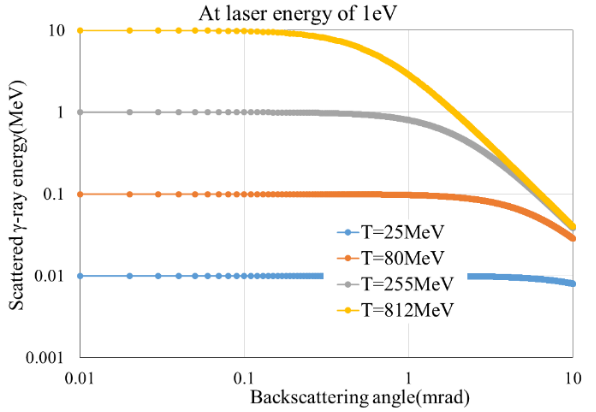

Fig. 3. LCS photon energy as a function of scattering angles at source laser energy of 1 eV

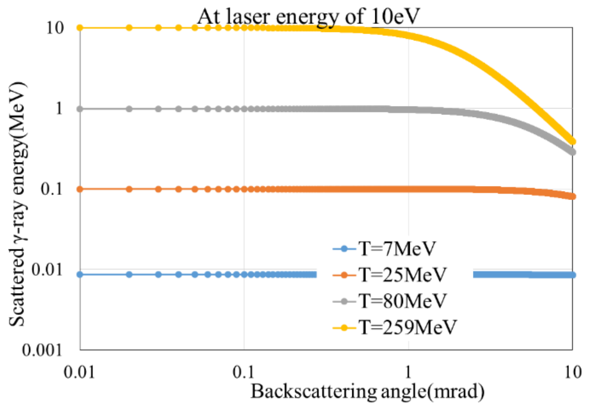

Fig. 4. LCS photon energy as a function of scattering angles at source laser energy of 10 eV

2.2 LCS photon energy in terms of laser and electron energies

Figure 5 shows LCS γ-ray energy as a function of the energy of laser and electron when the scattering angle is set constant at 0.01 mrad. The LCS γ-ray energy increases with both laser and electron energies, and it is a lot more sensitive to the electron energy.

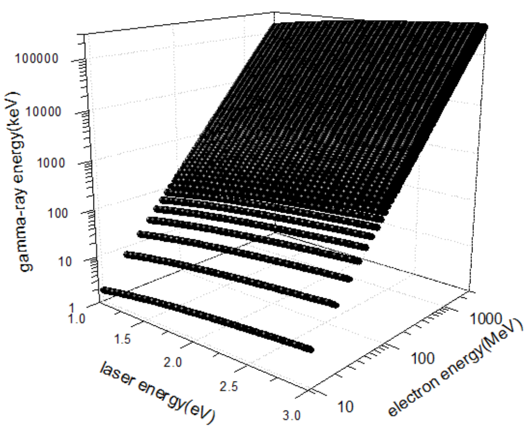

Fig. 5. LCS γ-ray energy as function of laser and electron energy.

3. Characteristics of the LCS Reaction Cross-section

Compton scattering cross-section from the electron at rest (ER) frame was developed by Klein-Nishina [5]. This model can be extended to the laboratory frame as:

$$\frac{d\sigma}{sin\theta d\theta} = \pi r_0^2 \frac{(1-\beta^2)}{(1-\beta cos\theta)^2} R^2 (R + \frac{1}{R} - 1 + \cos^2\theta'), \quad (3)$$

where r_0 is the classical electron radius (2.818 fm) [6],

$$R = \frac{E_\gamma^{ER}}{E_L^{ER}} = \frac{1}{1+(\frac{E_L^{ER}}{mc^2})(1+cos\theta')}, \quad (4)$$

$$E_L^{ER} = \frac{\sqrt{1-\beta^2}}{1-\beta} E_L, \quad (5)$$

$$cos\theta' = \frac{cos\theta - \beta}{1-\beta cos\theta}. \quad (6)$$

Total photon scattering cross-section for a cone angle θ_c using the laboratory frame is

$$\sigma(\theta_c) = \int_0^{\theta_c} d\theta \frac{d\sigma}{d\theta} \quad (7)$$

Average energy of γ-rays scattered into a cone angle θ_c in laboratory system can be determined as

$$E_\gamma^{av}(\theta_c) = \frac{\int_0^{\theta_c} d\theta E_\gamma(\theta)(d\sigma/d\theta)}{\int_0^{\theta_c} d\theta(d\sigma/d\theta)}. \quad (8)$$

Figure 6 depicts the Klein-Nishina Compton scattering cross-sections in terms of electron energy when the laser energy is set at 0.1 eV, 1 eV, and 10 eV. The Compton cross-section increases rather linearly with electron energy up to near 1 GeV. Beyond 1 GeV, the Compton scattering cross-section is almost saturated for laser energy of 0.1 eV and 1 eV, but clearly decreases for 10 eV laser energy. It is observed that the maximum cross-section is about 650 mb for the typical laser energy of up to a few eV.

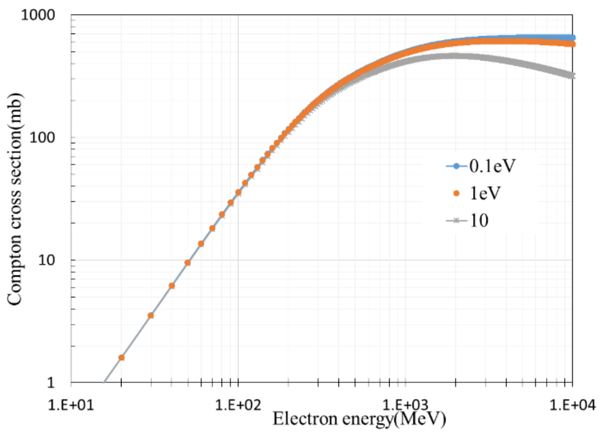

Fig. 6. Compton scattering cross-section in terms of electron energy for several laser energies.

4. The LCS γ-ray Intensity

The intensity of LCS photons scattered into a cone angle θ_c can be determined [3] by

$$I_\gamma(sec^{-1}) = \frac{(2.60) I_e(amps) P_L(Watts) L_L(cm) \sigma(mb)}{E_L(eV) A(cm^2)}, \quad (9)$$

where I_e is current of circulating electron, P_L is peak laser power during light pulse, E_L is laser photon energy, L_L is laser pulse length, σ is Compton cross-section from Eq. (7), and A is effective overlapped area between photon and electron at an interaction point given by

$$A = 2\pi\sqrt{\sigma_L^2 + \sigma_x^2} \cdot \sqrt{\sigma_L^2 + \sigma_y^2}, \quad (10)$$

where σ_L^2 is root mean square (RMS) radius of the laser beam, $\sigma_x^2$is RMS width of the electron beam and σ_y^2 is RMS height of the electron beam.

By way of an example, Figure 7 shows the intensity map of the LCS photons at the LADON-I facility in Frascati [3] in terms of laser and electron energies. It is worthwhile to note that the Ar-Ion laser used in the said facility is delivered at 20 W peak power in 450 cm-long laser pulses. The laser pulse was cylindrical with radius of $\sigma_L = 0.71$ mm. The electron beam was roughly rectangular, with $\sigma_x = 2.7$ mm $\sigma_y = 1.1$ mm, and stored current was 75 mA.

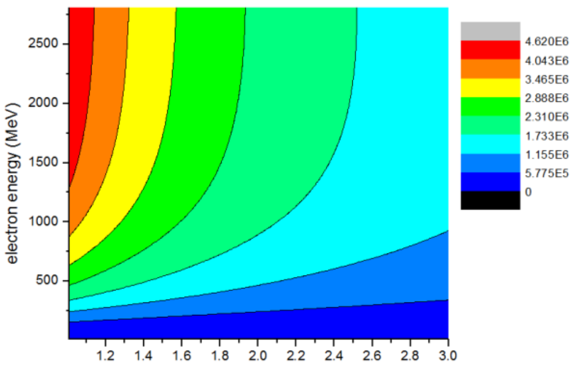

Fig. 7. Intensity map in unit of photons/sec in terms of laser and electron energies

As the Compton cross-section increases with electron energy, the laser intensity is also clearly high at high-electron energy. Similarly, as Compton cross-section decreases with increasing laser energy at high-energy electron, the resulting high-energy laser should be of lower intensity. Therefore using high-energy electron is more efficient than high-energy laser in producing the high-intensity high-energy LCS photon.

5. LCS Photon Production in Energy-recovery Linac System [2]

T. Hayakawa et al. [2] recently designed a high-flux LCS γ-ray facility utilizing a 350MeV energy-recovery linac (ERL) system. The facility was reported to yield a γ-ray intensity in order of 10^{13} photons/second, which is 10^5 to 10^6 higher than existing facilities around the globe listed in Table I. In Ref. 2, the total LCS photon flux was only considered, while mon-chromatic photon beam is of importance in actual applications. This work attempts to quantify the reported intensity using Eq. (9).

Table I. Compton Backscattering Facilities for the Generation of Gamma Beams Worldwide [7]

Facility name	Electron Energy (GeV)	Electron Current (A)	Beam intensity (photons/s)
LADON	1.5	0.05	5×10^5
LEGS	2.5	0.2	5×10^6
GRAAL	6	0.15	3×10^6
ELFE	15	0.05	10^7
SLEGS	3.5	0.3	1.95×10^9

Figure 8 depicts Hayakawa's ERL system. A 3-loop design is employed for cost reduction and compactness. An electron beam emitted from an injector is accelerated by a superconducting linac. After the three recirculation loops, the electron beam is re-injected into the linac with a deceleration phase, and the electron energy are fed back into RF cavity of the superconducting linac. LCS γ-rays are finally generated from collision of the electrons and the laser photons at the end of the loop. In this way, it was claimed that the length of the superconducting linac and its cost are roughly three times reduced.

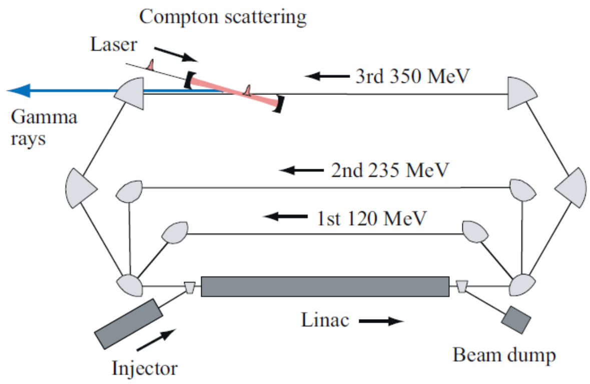

Fig. 8. Schematic of Hayakawa's ERL system [2].

In the study, high-flux γ-ray beams with energies of $E_\gamma = 0.5 - 9$ MeV are generated from the Compton scattering of a ytterbium-doped fiber laser with 80 MHz frequency, 100 W power. RMS of laser power density profile matches with RMS of the electron beam at the collision position: $\sigma_L = \sigma_x = \sigma_y = 70$ μm. The laser super-cavity is assumed to have an amplification factor of 3,000. In the case of γ-rays produced by collisions between laser photons with 1064 nm wavelength (equivalent to 1.165 eV photon energy) and electron energy of 350 MeV with a current of 100 mA, the maximum energy yield is $E_\gamma = 2.2$ MeV.

The reported E_γ value is in reasonable agreement with value of gamma-ray energy evaluated using Eq. (1), which predicts maximum E_γ of 2.179MeV. Note that the approximated scattering cross-section based on Thomson scattering cross-section was assumed to be $\sigma = \left(\frac{8}{3}\right)\pi r_0^2$ = 665 mb in Ref. 2. Meanwhile, the estimated cross-section with the Eq. (7) is 653 mb when the cone angle is π. With these approximated values, Eq. (9) predicts the resulting beam intensity to be 1.0×10^{10}photons/s. It should be noted that laser length was assumed to be 450 cm based on the reported values from the LADON facility [3]. This intensity value is 10^3 lower than what Hayakawa reported in his paper [2]. The discrepancy can however be explained if the amplification factor of the laser super-cavity, which can potentially be as high as 3,000 times larger, is considered. With this amplification factor, the resulting intensity predicted by Eq. (9) is about 3.0×10^{13}photons/s, which is in the same order of magnitude with what Hayakawa reported [2].

5.1 Intensity of Quasi-Monochromatic LCS Photons

In order to evaluate the intensity of a quasi-monochromatic LCS photon beam in the ERL system, the authors first changed cone angle in Eq. (9) from π rad to 1 mrad and 0.5 mrad. The analysis results are shown in Table 2. The LCS photon intensity changes to 1.0×10^{13} photons/sec and 4.6×10^{12} photons/sec, respectively. Averaged energy of γ-rays backscattered into cone angle θ_c in Eq. (8) are subsequently 1.856MeV and 2.057MeV for 1 and 0.5mrad, respectively. In comparison against 1.084MeV for θ_c of π rad, the average energy for the two cone angles are much higher and quite similar.

Table 2. Intensity as function of cone angles and their averaged energy

Electron energy (MeV)	Laser energy (eV)	Cone angle (mrad)	Intensity (Photons/sec)	Average energy (MeV)
350	1.165	0.5	4.6×10^{12}	2.057
		1.0	1.0×10^{13}	1.856
		$\pi \times 10^3$	3.0×10^{13}	1.084

Table 3. Intensity in terms of laser and electron energy for a cone angle of 1mrad

Cone angle (mrad)	Electron energy (MeV)	Laser energy (eV)	Intensity (Photons/sec)
1	350	0.582	2.3×10^{13}
	250	1.165	7.8×10^{12}

The resulting LCS photon intensity when its energy is halved (i.e. from 2.2 MeV to 1.1 MeV) was also estimated. For this, the authors first changed laser energy from 1.165 to 0.582 eV and set the electron energy at 350 MeV and the results are provided in Table 3. With these values, the predicted LCS photon intensity is 2.3×10^{13} photons/sec. When the electron energy is reduced from 350 MeV to 250 MeV and set the laser energy at 1.165 eV, the LCS photon intensity becomes 7.8×10^{12} photons/sec. This is in agreement with our observations on Compton cross-section characteristics. When electron energy is doubled to 750 MeV, the maximum LCS photon energy is 8.65 MeV with intensity of 1.9×10^{13} photons/sec. Figure 10 shows the spectrum of the quasi-monochromatic LCS photon beams.

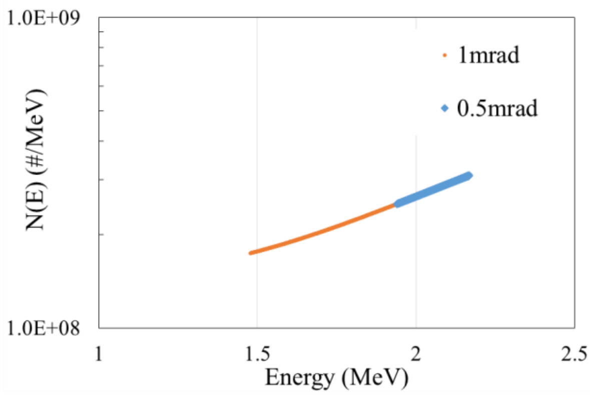

Fig. 10. LCS photon energy spectrum for two cone angles (0.5 mrad, 1 mrad).

6. Conclusions

This paper presents essential characteristics of the laser Compton scattering (LCS) in terms of its photon energy, cross-section and photon intensity. By using different combinations of electron energy, laser energy and scattering angle, we can effectively generate high-intensity and highly-chromatic LCS gamma-rays. Our preliminary analyses indicate that, in view of Compton cross-section, higher-energy photon can be better generated by increasing the electron energy rather than increasing the laser energy. However, in order to maximize the intensity of monochromatic beam, the laser energy should be maximized for a targeted LCS photon energy. In addition, it is important to note that 2 MeV photon with an intensity as high as 1.0×10^{13}photons/s can potentially be produced in the near future. And it is expected that a much higher LCS photon intensity can be available through optimization of the facility.

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