GENERATION OF HIGH-BRIGHTNESS GAMMA-RAYS FROM ENERGY-RECOVERY LINAC

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Abstract

Energy-recovery linac (ERL) to generate an electron beam of small emittance and high-average current is a suitable driver for laser Compton scattered γ-ray sources (LCS γ-ray). A combination of an ERL and a laser enhancement cavity will improve the performance of LCS γ-ray significantly in comparison with existing LCS sources based on linac and storage rings. Accelerator technologies relevant to ERL LCS sources, small-emittance gun and superconducting cavities, are same as ERL X-ray sources. We plan to demonstrate high-brightness LCS photon generation at the Compact ERL.

LASER COMPTON SCATTERED GAMMA-RAY SOURCES

The combination of an energy-recovery linac and a high-power mode-locked laser realizes significant improvement of γ-ray sources based on laser Compton scattering (LCS).

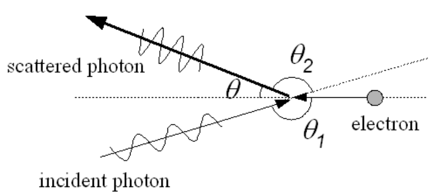

Figure 1: Laser Compton scattering.

Figure 1 shows a schematic representation of laser Compton scattering, where a high-energy photon (γ-ray) is generated via the Compton back-scattering of an incident laser photon with a relativistic electron [1]. The energy of the scattered γ-ray photon, E_g, is a function of the incident photon energy, $E_L = hc/\lambda$, electron energy $E_e = \gamma mc^2$, and scattering geometry, and approximated for a head-on collision:

$$E_g \approx \frac{4\gamma^2 E_L}{1+(\gamma\theta)^2 + 4\gamma E_L/(mc^2)} \quad (1)$$

The above equation shows that the γ-ray energy has a correlation to the scattered angle. Therefore, monochromatic γ-rays can be obtained by putting a collimator to restrict the γ-ray divergence at the downstream. Owing to the energy tunable monochromatic γ-ray generation, LCS γ-ray sources have been developed by using storage rings and linacs [2-5].

A γ-ray flux from Compton scattering at an ideal head-on geometry integrated over the entire scattering angle is given by

$$F_{total} = \frac{f N_e N_L \sigma_C}{A} , \quad (2)$$

where f is the collision frequency, N_e is the number of electrons in an bunch, N_L is the number of photon in a laser pulse, σ_C is the cross-section of Compton scattering, A is the effective sectional area of beams at the collision point. In order to obtain a high-flux γ-ray, it is necessary to increase the density of both electrons and photons at the collision point. As seen in the above equation, an electron beam of small emittance and high-average current is essential to high-flux γ-ray generation via Compton scattering. The combination of an ERL and a laser enhancement cavity is, thus, a promising source of high-flux γ-rays [6,7].

Figure 2 shows a schematic view of an ERL γ-ray source. At the collision point, electron bunches circulating the ERL loop collide with laser pulses stored in an enhancement cavity, which is a high-finesse Fabry-Perot optical resonator to stack a train of laser pulses from a mode-locked laser [8].

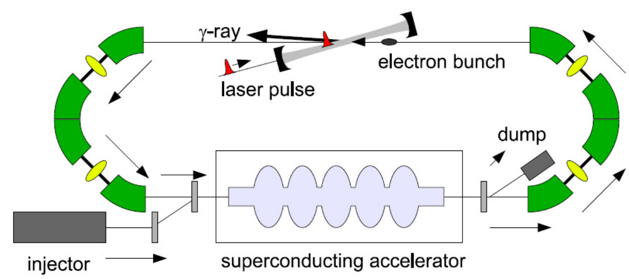

Figure 2: A schematic view of LCS γ-ray source based on an ERL and a laser enhancement cavity.

As shown in Eq. (1), γ-ray energy has a correlation with the scattering angle. However, this correlation becomes imperfect due to inhomogeneous effects of electron and laser beams. In the case of the head-on collision, the bandwidth of scattered γ-rays observed on the electron beam axis, $\theta = 0$, can be calculated by assuming the laser spot size w ($1/e^2$ radius) and the electron beam spot size σ ($1/e$ radius) as follows [9]:

$$\left(\frac{\Delta E_g}{E_g}\right)^2 = \left(\frac{\Delta E_L}{E_L}\right)^2 + \left(\frac{2\Delta E_e}{E_e}\right)^2 + \frac{1}{4}\left(\frac{\lambda}{\pi w}\right)^2 + 4\left(\frac{\varepsilon_n}{\sigma}\right)^4 \quad (3)$$

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where the first term in the right-hand side is the spectral broadening due to the bandwidth of the incident laser pulse, the second term is the electron beam energy spread, the third term is the divergence of the laser beam, and the last term is the divergence of the electron beam due to a finite emittance.

The effect of electron beam emittance on the broadening of γ-ray bandwidth becomes as small as the effect of laser diffraction, when we have a normalized emittance: $\varepsilon_n = \lambda/4\pi$. From this criterion, we can define the "diffraction limited" electron beam. For a typical laser wavelength, 1 µm, the diffraction limited electron beam for LCS γ-ray sources has a normalized emittance of 0.08 mm-mrad, which is a similar value to the required emittance for ERL-based synchrotron radiation sources to obtain coherent hard X-rays. Consequently, we can share accelerator components such as electron injector and accelerator for both ERL-based X-ray sources and ERL-based γ-ray sources.

Table 1: Parameters for a 2-MeV γ-ray source. Two operation modes are considered: high-flux mode (100 pC, 1 mm-mrad) and narrow-bandwidth mode (10 pC, 0.1 mm-mrad).

ERL electron beam		**Laser**	
Energy (MeV)	350	Wavelength (nm)	1064
Bunch charge (pC)	10 / 100	Pulse energy (µJ)	1.5
Repetition (MHz)	130	Repetition (MHz)	130
Bunch length (rms, ps)	3	Pulse length (rms, ps)	3
Norm. emittance (mm-mrad)	0.1 / 1.0	Enhancement	2000
Energy spread (rms)	0.03%	Intracavity power (kW)	400
Collision spot (rms, µm)	10	rms Collision spot (rms, µm)	10
Collision angle (degree)	3.5		

Table 1 shows an example set of parameters for 2-MeV γ-ray source designed for nuclear material measurement [10]. The γ-ray source is operated at two different modes: high-flux mode (100 pC, 1 mm-mrad, 130 MHz) and narrow-bandwidth mode (10 pC, 0.1 mm-mrad, 130 MHz). The collision laser is assumed to be a 200 W average power and the laser cavity has an enhancement factor of 2000, which accumulates 400 kW intra-cavity laser power. The collision spot size is 10 µm (rms) for the electron and laser beams. In the high-flux mode, the LCS source produces a γ-ray with a total flux of 1.0×10^{13} ph/s as shown in Fig. 4, where the γ-ray spectrum is calculated by Monte Carlo simulation code CAIN [11]. Narrowband γ-rays are obtained by placing an on-axis collimator on the γ-ray beam line. Figs. 4 and 5 show γ-ray spectra with various sizes of collimators for the high-flux and narrow-bandwidth modes, respectively. It is clearly seen that the diffraction-limited electron beam (normalized emittance of 0.1 mm-mrad) contributes to the significant improvement in the γ-ray bandwidth. In the narrow-bandwidth mode with a 0.05-mrad aperture, the γ-ray bandwidth is 0.2% (FWHM). In the limit of small aperture at the narrow-bandwidth mode, the γ-ray bandwidth is restricted by electron beam energy spread. Possible use of low-frequency spoke cavities achieves further reduction of LCS γ-ray bandwidth because of the smaller RF-correlated energy spread of electron beams [12].

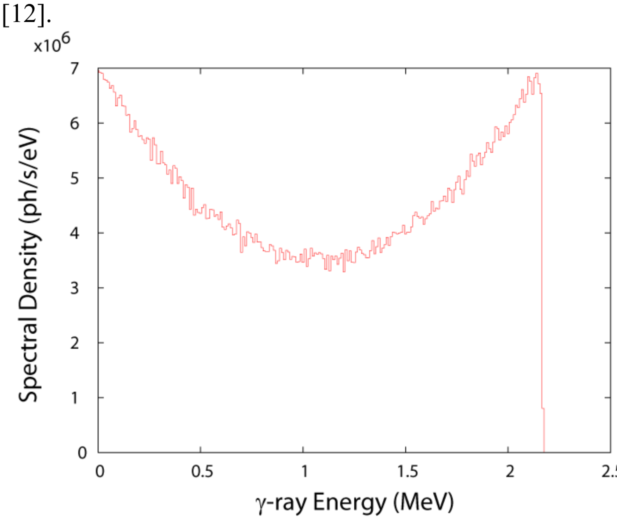

Figure 3: Calculated γ-ray spectrum for the high-flux mode of the designed ERL γ-ray source. The total flux is 1.0×10^{13} ph/s.

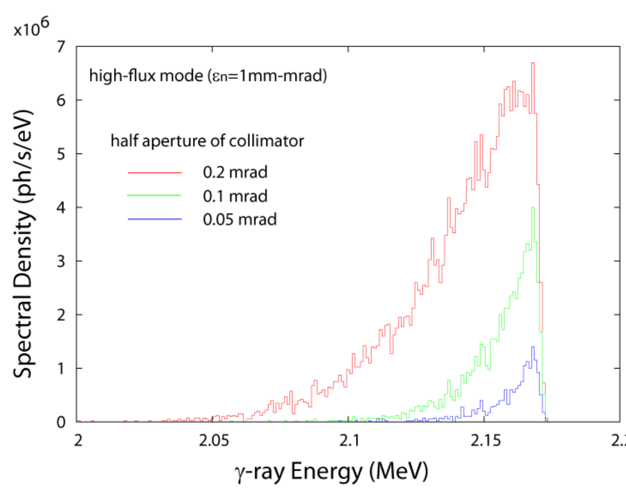

Figure 4: Calculated γ-ray spectrum for the high-flux mode with various sizes of on-axis collimators. Collimator half aperture is 0.2 mrad, 0.1 mrad and 0.05 mrad.

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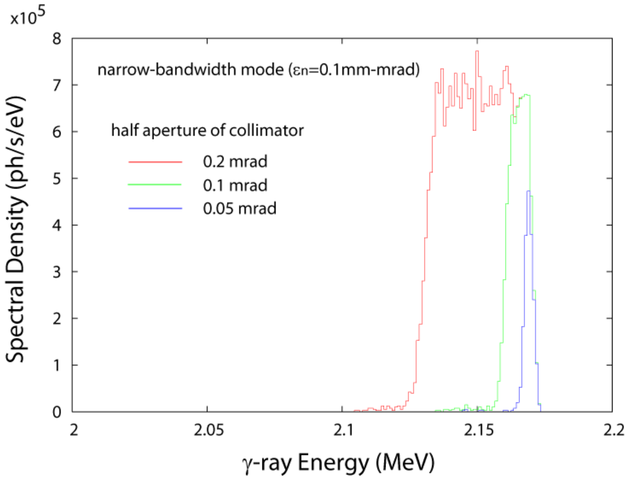

Figure 5: Calculated γ-ray spectrum for the narrow-bandwidth mode with various sizes of on-axis collimators. Collimator half aperture is 0.2 mrad, 0.1 mrad and 0.05 mrad.

An electron beam in a LCS γ-ray source suffers from quantum excitation from collision with laser photons. This quantum excitation causes growth of emittance and energy spread of the electron beam. Degradation of electron beam quality, growth of emittance and energy spread, is summarized in ref [13]. The growth of normalized emittance after a collision is given by

$$\Delta(\varepsilon_n) = \frac{3}{10}\frac{\lambda_c}{\lambda_L}\frac{\Delta E_\gamma}{E}\beta^* \quad , \tag{4}$$

where $\lambda_c = h/mc = 2.43\text{x}10^{-12}$ m is the Compton wavelength of the electron, λ_L is the laser wavelength, β^* is the betatron function at the collision point, ΔE_γ is the energy loss of the electron after the collision. For the designed 2-MeV γ-ray source operated at the narrow-bandwidth mode, we find ΔE_γ=2.0 keV and $\Delta(\varepsilon_n)=2.7\text{x}10^{-12}$ m-rad.

The electron energy spread induced by laser Compton scattering is calculated by

$$\Delta(\sigma_E) = \sqrt{\frac{7}{10}\hbar\omega_m\Delta E_\gamma} \quad , \tag{5}$$

where $\omega_m = 4\gamma^2\omega_L$ is the maximum γ-ray photon frequency. For the designed 2-MeV γ-ray source operated at the narrow-bandwidth mode, we have $\Delta(\sigma_E)$=56 keV.

The above estimation of spent beam quality suggests that we may install multiple interaction points along an ERL return loop to accommodate several γ-ray beam lines without degradation of γ-ray brightness and bandwidth.

Note that a LCS γ-ray source based on a storage ring has a limitation of γ-ray bandwidth resulting from a large energy spread of electrons at the equilibrium state, where the quantum excitation is balanced with the longitudinal damping. The electron energy spread at the equilibrium state of a storage ring is given by [13]

$$\left(\frac{\sigma_E}{E}\right)_{eq} = \sqrt{\frac{7}{5}\frac{\lambda_c}{\lambda_L}\gamma} \quad . \tag{6}$$

In a 350-MeV storage ring operating with a 1 μm laser to produce 2-MeV γ-rays, the electron energy spread at the equilibrium state is calculated to be 4.6% (rms).

As we have seen, ERL is an ideal electron accelerator for laser Compton scattering light source to produce γ-rays of high flux and narrow bandwidth. Electron beams of small emittance and high-average current available from ERLs realize unprecedented light sources in photon energies of MeV, γ-rays, as well as X-rays. The improvement of γ-ray performance from the existing LCS γ-ray sources includes the enhancement of flux by 5-8 orders and the bandwidth narrowing by 1-2 orders. Such γ-ray sources are of great use in many scientific and industrial applications: nuclear physics [14], nuclear astrophysics [15], hadron physics [16], management of nuclear waste [17], nuclear security and safeguards [18].

In order to demonstrate the performance of ERL γ-ray source and explore applications of ERL γ-ray sources to nuclear security and safeguards purposes, JAEA has launched a 3-year program (2011-2013) supported by Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan [19]. The program aims at generation of a high-flux and narrow-bandwidth γ-ray beam at the Compact ERL in collaboration with KEK. Application of the γ-ray to non-destructive measurement of isotopes is also planned. Figure 6 shows a schematic view of the proposed experiment at the Compact ERL.

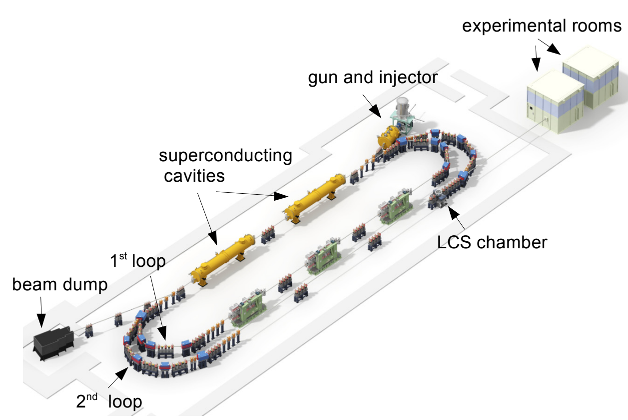

Figure 6: A schematic view of the LCS γ-ray experiment at the Compact ERL.

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