LINAC-BASED LASER COMPTON SCATTERING X-RAY AND GAMMA-RAY SOURCES

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Abstract

Laser Compton scattering (LCS) light sources can provide high-energy photons from keV to MeV range. Many research and development projects of linac-based LCS sources are carried on. For the photon energies of tens keV, linac-based LCS sources realize laboratory-size X-ray sources, of which performance is potentially comparable to 2nd generation synchrotron light sources. Linac-based LCS also realizes unparalleled γ-ray sources of high-brightness and narrow bandwidth. In the present paper, status and perspectives of linac-based LCS X-ray and γ-ray sources are reviewed.

LASER COMPTON SCATTERED PHOTON SOURCES

The combination of a high-energy electron accelerator and a laser realizes high-energy photon sources based on laser Compton scattering (LCS) [1].

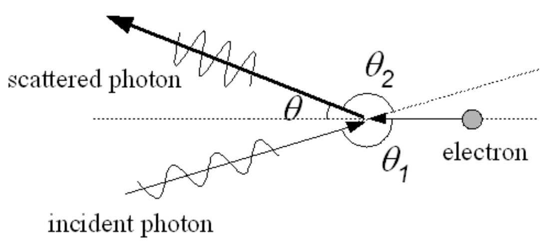

Figure 1: Laser Compton scattering.

Figure 1 shows a schematic representation of laser Compton scattering, where a high-energy photon (X-ray or γ-ray) is generated via the Compton back-scattering of an incident laser photon with a relativistic electron. The energy of the scattered photon, E_x, 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:

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

The above equation shows that the LCS photon energy is tunable by changing electron beam energy, laser wavelength or collision angle. The LCS photon energy also has a correlation to the scattered angle. Therefore, monochromatic photon beam can be obtained by putting a collimator to restrict the LCS beam divergence at the downstream. We can produce linear- and circular-polarized high-energy photons by using polarized lasers. The electron energy necessary for generation of hard X-ray (20 keV, for example) is only 30 MeV, which is much smaller than the electron energy to produce hard X-ray via synchrotron radiation.

Owing to the above features of LCS photon source, energy tunability, monochromatic and polarized photon generation, compactness, LCS sources have been developed by using various types of accelerators such as storage rings, linacs and microtron [2-6]. In the present review, we focus on linac-based LCS photon sources in X-ray and γ-ray energies.

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

$$F_{total} = \frac{16}{3} N_e N_L f \frac{r_0^2}{w_0^2} \quad (2)$$

where N_e and N_L are the number of electrons and laser photons at the collision, respectively, f is the collision frequency, r_0 is the electron classical radius and w_0 is the collision spot size.

Spectral brightness of laser Compton scattered photon sources can be calculated as

$$B \approx F_{total} \frac{\gamma^2}{\varepsilon_n^2} \times 0.1\,\% \quad (3)$$

where ε_n is normalized emittance and the factor 0.1% is for the conventional unit of spectral brightness, (photons/sec/mm^2/mrad^2/0.1%BW).

In order to obtain a high-flux and high-brightness photon beam from laser Compton scattering, it is necessary to increase the density of both electrons and photons at the collision point and to reduce normalized emittance. An electron beam of small emittance and high-average current is, thus, essential to high-flux and high-brightness photon generation via laser Compton scattering.

LINAC-BASED LCS X-RAY SOURCES

Linac-based LCS X-ray source enable us to produce energy-tunable X-ray beams with a laboratory-size apparatus, of which flux and brilliance is potentially comparable to synchrotron radiation from a bending magnet of GeV-class storage rings. There are many R&D programs carried out for realizing LCS X-ray sources. Here, we see research activities on-going in Japan.

A LCS X-ray source has been developed at AIST (National Institute of Advanced Industrial Science and Technology) [7]. They employed a 42-MeV S-band linac equipped with a photocathode RF gun. For the laser Compton scattering, they use a Ti:Sapphire laser. Two

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collision angles, 90-degree and 165-degree, are possible to generate LCS X-rays. Ultrashort X-ray pulses, 150 fs (rms), are obtained at the 90-degree collision and a high-flux X-ray, 10^7 photons/s, is available at the 165-degree collision. The LCS X-ray source has been used mainly for imaging applications such as phase contrast imaging of rat's lumber vertebra [8] and K-shell absorption angiography of rabbit [9]. In order to improve X-ray flux, they are developing a multi-collision system, in which a train of electron bunch generated from the photocathode gun collides with a train of laser pulse to produce LCS X-rays with a flux of 3.3×10^9 photons/s [10].

There are two LCS X-ray source under development at High Energy Accelerator Research Organization (KEK). One is based on an S-band normal conducting linac and the other is based on an L-band superconducting linac. Both the LCS sources are utilizing multi-collision configuration. The S-band LCS source named LUCX (Laser Undulator Compact X-ray) has already demonstrated X-ray generation and imaging application [11]. They obtained an X-ray beam at 30 keV with a flux of 2.1×10^5 photons/s.

The superconducting LCS X-ray source at KEK is based on an L-band superconducting linac originally developed for ILC (International Linear Collider). They have constructed an electron beam transport line for the LCS X-ray generation at the downstream of an ILC cryomodule [12]. A 4-mirror type laser enhancement cavity is employed for the multi-collision LCS X-ray generation. Generation of electron bunch, 162500 bunches in a train of 1-ms duration, has been successfully demonstrated [13]. The first X-ray generation is scheduled by the end of 2012 using a 40-MeV electron beam. Expected performance of LCS X-ray is energy of 30 keV and flux of 1.4×10^{11}photons/s/10%BW.

Table 1 is a summary of the LCS X-ray sources in Japan, where the average spectral brightness is evaluated by Eqn.(3) with assuming normalized emittance of 1 mm-mrad, a typical value obtained from a photocathode electron gun.

Table 1: Linac-based Laser Compton X-ray sources

Facility	X-ray Energy	X-ray Flux #1	X-ray Brightness #2
AIST (demonstrated)	40 keV	10^7	$\sim10^8$
AIST (upgrade)	38 keV	3.3×10^9	$\sim10^{10}$
LUCX (demonstrated)	30 keV	2.1×10^5	$\sim10^6$
STF (design)	30 keV	1.4×10^{12}	$\sim10^{13}$

#1 photons/sec/100%BW

#2 photons/sec/mm^2/mrad^2/0.1%BW, evaluation by Eq. (3) with assuming a normalized emittance of 1 mm-mrad

From Table 1, we can see that linac-based LCS X-ray sources are surpassing the brightness of X-ray tubes and approaching to the brightness of bending magnet radiation from a 2nd generation synchrotron light source.

LINAC-BASED LCS GAMMA-RAY SOURCES

Since synchrotron radiation light sources cannot cover photon energies above ~1MeV, LCS is the only photon source to produce energy-tunable photon beams in MeV energy region. So far, LCS γ-ray sources have been developed utilizing storage rings [2,3].

Storage-ring based LCS γ-ray sources, however, have a limitation of spectral brightness due to quantum excitation. An electron beam in a LCS photon 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 [14]. In the limit of high-density collision, energy spread of an electron beam in a storage ring LCS source reaches to an equilibrium, where the quantum excitation balances with the radiation dumping:

$$\left(\frac{\sigma_E}{E}\right)_{eq}=\sqrt{\frac{7}{5}\frac{\lambda_c}{\lambda_L}\gamma} \tag{4}$$

where $\lambda_c=h/mc=2.43\times10^{-12}$ m is the Compton wavelength of the electron, λ_L is the laser wavelength. For example, in a 350-MeV storage ring operated with a 1 μm laser to produce 2-MeV γ-rays, the electron energy spread at the equilibrium is calculated to be 4.6% (rms). This growth of energy spread becomes a serious limitation of spectrum brightness of storage ring-based LCS γ-ray sources.

According to Eq. (3), the spectral brightness of LCS photon source is proportional to γ^2 as far as the normalized emittance is preserved. In order to receive the full benefit of γ^2 scaling, linac is the best platform for LCS γ-ray source. An electron beam preserves its normalized emittance during acceleration in a linac and the electron beam after the LCS interaction goes to a beam dump, thus, we can keep the collision of fresh electrons with laser photons to produce high-flux and high-brightness γ-rays in linac-based LCS sources.

In Lawrence Livermore National Laboratory (LLNL), they have developed a linac-based LCS γ-ray source, T-REX, for a homeland security application, which is detection of special nuclear material hidden in a cargo container [15]. The detection is based on nuclear resonance fluorescence (NRF), isotope specific photonuclear reaction [16]. The γ-ray source, T-REX, utilized a 120-MeV S-band normal conducting linac equipped with a photocathode RF gun. They generated γ-rays, 200-500 keV, from T-REX and demonstrated the detection of concealed material of a specific isotope, Li-7 beyond a shield, by using 478 keV γ-ray from T-REX [17].

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Following the successful demonstration of LCS γ-ray generation at T-REX, a new LCS γ-ray source, VELOCIRAPTOR, is under development at LLNL [18]. For the γ-ray source, VELOSILAPTOR, they employed an X-band linac developed by SLAC for making the γ-ray source compact. Since the fissile isotopes, U-235 and Pu-239, have resonant energy around 2 MeV, they chosen machine parameters to produce 2 MeV γ-rays. An electron beam from the X-band linac has energy of 250 MeV to produce 0.5-2.5 MeV γ-ray by collision with frequency-doubled Nd:YAG laser.

In the detection of nuclear material using NRF, narrow-band γ-rays are essential for the better signal-to-noise ratio in the measurement, because the resonant width of NRF is less than 1 eV and incident γ-rays out of this resonant width become background noise. In LLNL, they optimized electron beam parameters to obtain narrow-band γ-rays [19].

In Japan, another application of LCS γ-ray has been proposed, which is non-destructive measurement of fissile material in melted nuclear fuel at Fukushima Daiichi Nuclear Power Plant [20]. The Great East Japan Earthquake on March 11, 2011 brought a severe accident in Fukushima Daiichi Nuclear Power Plant. Most of nuclear fuels in the plant has been melted due to loss of coolant. It is currently being thought that the complete decommissioning of the plant will take 30-40 years. During this long-term decommissioning process, the removal of melted fuels will most probably start from 2021 or later and will continue for 10-15 years. In this removal process, it is considered that debris of melted fuel are contained in a water-filled canister. Under the nuclear safeguards agreement, we need to measure the amount of fissile material in each canister to declare no fissile material is diverted into a weapon. Taking into consideration the available time prior to the removal of the melted fuel from the reactors, we have time to develop some techniques for the measurements of fissile material in the melted fuels.

A research group of JAEA proposed a non-destructive measurement system for plutonium in spent nuclear fuel by nuclear resonance fluorescence triggered by LCS γ-ray source based on an energy-recovery linac (ERL) [21,22]. It is considered that the ERL γ-ray source is also applicable to the measurements of fissile material in the melted fuel.

In order to demonstrate the performance of ERL LCS γ-ray source for the application of nuclear material measurement, JAEA has launched a 3-year R&D program (2011-2013) supported by Ministry of Education, Culture, Sports, Science and Technology (MEXT) in Japan [20]. The program aims at generation of a high-flux and narrow-bandwidth LCS photon beam at the Compact ERL in collaboration with KEK. Figure 2 shows a schematic view of the proposed experiment at the Compact ERL. Since the initial commissioning of the Compact ERL is conducted at electron beam of 35 MeV and 10 mA, generated LCS photon energy will be 22 keV and the flux is expected to be ~10^{11} photons/sec.

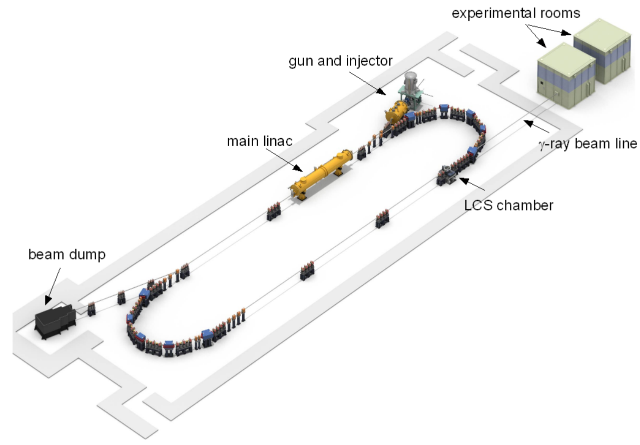

Figure 2: A schematic view of the LCS γ-ray experiment at the Compact ERL

For the measurement of fissile material, 2-MeV γ-rays are required to cover NRF energies of uranium and plutonium isotopes. For this purpose, a 350 MeV ERL to produce 2-MeV γ-ray at a flux of 10^{13} photons/sec was designed [23]. For the more compact and efficient LCS γ-ray source, utilization of a multi-turn ERL with spoke cavities operated at 4K is also under consideration.

LCS γ-ray source will be an innovative tool for scientific applications as well. A research facility of LCS γ-ray is to be built at Bucharest, Romania. The facility is ELI-NP (ELI Nuclear Physics), which is one of the four pillars of Extreme Light Initiative (ELI), pan-European laser facility aiming to host the most intense lasers world-wide [24].

The ELI-NP is a complex facility of petawatt lasers and LCS γ-rays, where two 10-petawatt class lasers and a 600-MeV linac for LCS γ-rays are constructed in the same facility. In the Whitebook of ELI-NP, many experimental proposals are described [25], for example, probing the pair creation from the vacuum in the focus of strong electrical fields with a high energy γ-ray beam, which is a validation of QED. Production of medical isotope using narrow-band γ-ray beam is also proposed at ELI-NP [26].

SUMMARY

The performance of linac-based LCS X-ray and γ-ray sources shows continuous improvement following advancement of laser and accelerator technologies. LCS X-ray source is able to provide energy-tunable, polarized and quasi-monochromatic hard X-rays with a laboratory-size apparatus. Spectral brightness of recently developed LCS X-ray source exceeds the brightness of X-ray tubes. The flux and brightness can be further increased by multi-collision configuration. Expected performance of curently-developing LCS X-ray source is comparable to bending magnet radiation from 2nd generation synchrotron sources.

LCS also provides energy-tunable narrow-bandwidth γ-rays in photon energies above 1 MeV, where synchrotron radiation source is not available. Since a linac is free from electron beam degradation due to accumulation of the quantum excitation, linac-based γ-ray source is unparalleled in terms of its narrow bandwidth and spectral brightness. Development of LCS γ-ray sources are carried out in the world towards homeland security, nuclear industrial applications and innovative science.

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