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Experiment of X-ray Generations Using Laser-Compton Scattering at LINAC of SINAP*

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Abstract: Laser Compton scattering(LCS) can generate X-rays or γ-rays with high brightness and easy controlled polarization by applying high-peak-power laser pulses to relativistic electron bunches. One of the most promising approaches to short pulsed X-ray sources is the laser synchrotron source. It is based on LCS between picoseconds relativistic electron bunches and picoseconds laser pulses. A project of Shanghai laser electron gamma source with LCS method has been proposed on Shanghai synchrotron radiation facility. Before that, a prototype has been developed in the beamline of the linear accelerator at the Shanghai Institute of Applied Physics, Chinese Academy of Sciences. The LCS experiment was carried out by using the 107 MeV, 5 Hz, 1 ns, 0.1 nC electron bunches from the linear accelerator and the 18 ns, 10 MW peak power, Nd∶YAG laser pulses. In this communication, we describe the details and report the first results of this experiment.

Key words: Compton scattering; Nd∶YAG laser; γ-ray source; polarization

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1 Introduction

Bright and tunable short pulse X-ray sources are being widely used in various novel scientific and industrial fields including medical, chemical, biological, material, and industrial fields. Sub-picosecond X-ray processes are of great interest because, for example, they can probe lattice vibration phenomena over a single oscillation or, for another example, because they can "image" bio-molecular reactions as they occur. Potential study topics using these X-ray sources include lattice vibration measurements, time-resolved chemistry, microprobe, and 3-D motion of atoms. Existing synchrotron light sources are several orders of magnitude away from this possibility. Laser Compton scattering (LCS) is one of the most exciting methods used to generate such short-pulse X-rays.

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In 1963, Milburn[1] and Arutyunian and Tumanian[2] originally proposed the LCS scheme and accurately predicted the production of quasimonochromatic photon beams by utilizing laser backscattered photons from an energetic electron beam. The basic properties of laser Compton X-rays, such as the photon energy and divergence, have been well studied, both theoretically[3, 4] and experimentally[5−8]. These properties are characterized by the Lorentz factor of the electrons (γ), namely, the ratio of the electron energy to the electron rest mass. When photons interact with high energy moving electrons, the electrons scatter low energy photons to a higher energy at the expense of the electrons' kinetic energy. This interaction results in the emission of highly directed (peaked in the direction of the incident electron beam), mono-energetic, highly polarized and tunable X-ray beams with a divergence on the order of a vertex angle of $1/\gamma$. The laser Compton X-ray energy is spread in the region between 0 and $2\gamma^2 E_\mathrm{L}$ (E_L: laser photon energy) in the 90° interaction geometry. However, monochromatic photons can be easily obtained because the photon energy is determined uniquely by the scattering angle. Therefore, high-energy electron beams produce good-directionality photons by LCS.

Shanghai Synchrotron Radiation Facility[9], SSRF, is a third-generation of synchrotron radiation light source and will be put into operation by Apr. 2009. The energy of electron bunches in the storage ring is 3.5 GeV, which is the highest value in the medium-energy light source in the world. In our project of Shanghai Laser Electron Gamma Source (SLEGS), γ-ray with energy of up to 22 MeV will be generated by using LCS method[10]. SLEGS will be built at the 20th straight sections of the SSRF storage ring. As a prototype of SLEGS, an X-ray source based on LCS method has been installed at the terminal of a 100 MeV RF linear accelerator (LINAC) at Shanghai Institute of Applied Physics (SINAP). The LCS experiment has been carried out by using the 107 MeV, 5 Hz, 1 ns, 0.1 nC electron bunches from LINAC and the 18 ns, 10 MW peak power, Nd:YAG laser pulses. The produced X-ray with energy of 29 keV has been observed. In this paper, the experimental details were described and the preliminary results were represented.

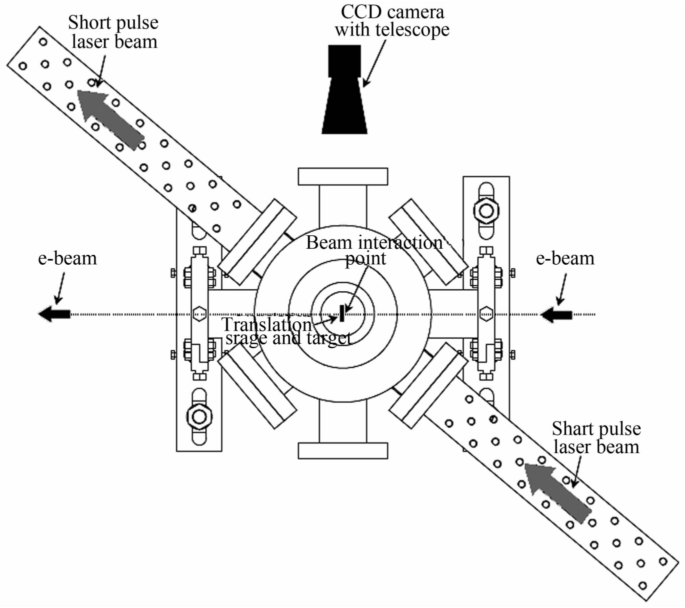

Fig. 1　Top view of the Compton chamber.

2 Experimental Set-up

We have developed a LCS chamber for the proof-of-principle experiment, in which counter propagating electron and Nd∶YAG laser pulses collide at the focal point. Fig. 1 shows the drawing of the Compton chamber installed in the LINAC beamline of SINAP. Short-pulsed Nd∶YAG laser beam can be introduced through three side windows with the angle between the laser and electron beam of 40°, 90° and 140°, respectively. At the first stage of our experiment, the angle of interaction between the short pulse laser light and the electron beam was set at 40°, as shown in Fig. 1. A parabolic Cu mirror of the 50 mm diameter with the focal length of 15 cm focuses the laser beam at the colliding point.

Fig. 2 shows the general arrangement of the experimental set-up, which contained an electron beam source, a light source and an X-ray beam monitor. The LINAC produces an electron beam. Electron bunches with the charge of about 0.1 nC within a 1—2 ns (rms) bunch length are generated by a photo-cathode RF gun at a 5 Hz repetition rate. They are accelerated up to 107 MeV in the RF LINAC by a 2 856 MHz klystron and transported by using bend magnets and quadrupoles to the Compton chamber. The electron beam is focused on the center of the chamber, where it scattered against the laser beam, by using the four-quadrupole magnets. Some steering magnets combined in the quadrupole magnets are used to adjust the beam's position. After the Compton chamber, a 30°-bending magnet deflected the electron beam onto a beam dump, away from the forward scattered X-rays.

To measure the spot size (and position) of the electron beam and the laser beam at the interaction

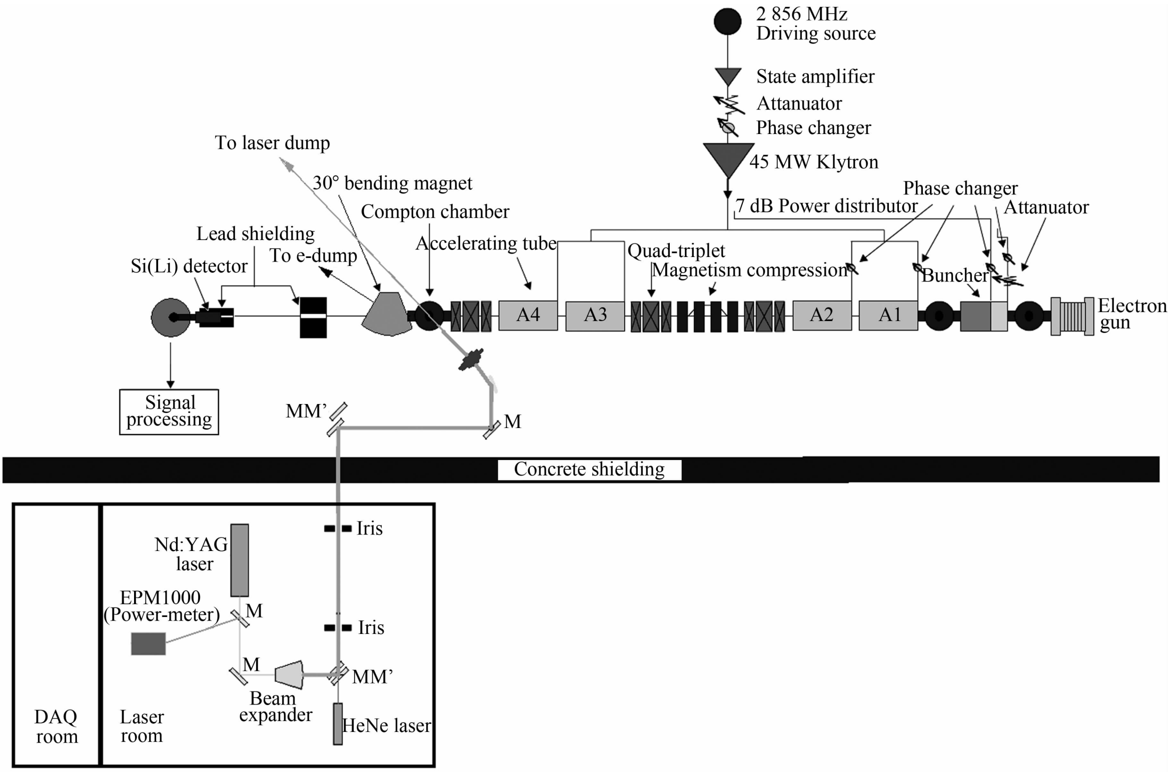

Fig. 2 General arragment of the experimental set-up, which contained an electron beam source, a Laser system and an X-ray beam monitor. A combination of a RF photocathode and a LINAC was used for the electron beam source. A pulsed Nd∶YAG laser system was used for the intersction with the electron beam. The repetition rates of e-bunch and laser pulse are 5 and 2.5 Hz, respectively. This was synchronized to the RF of the electron beam, which was 2 856 MHz.

point, a 2 mm thick phosphor foil, mounted on a retractable plunger at 45° with respect to the beam, was installed in the chamber, as shown in Fig. 3(a). An image of the electron beam was obtained from optical transition radiation. The image was relayed onto a 16 bit Charge-Coupled Device (CCD) camera. From this interaction geometry, electron beam spot sizes as small as approximately 8 mm ×4 mm have been measured at the colliding position. One of them is shown in Fig. 3(b).

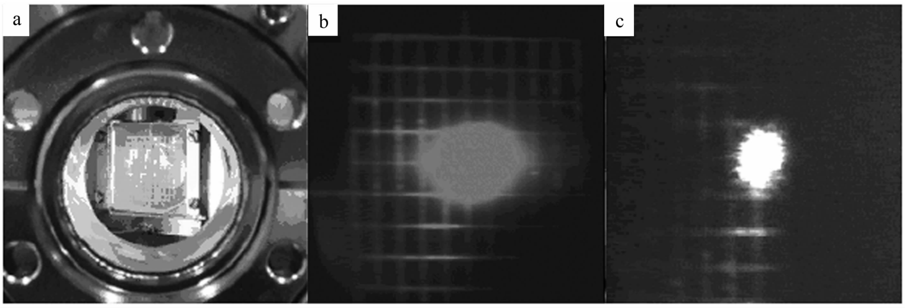

Fig. 3 The photo of the 2 mm thick phosphor foil mounted inside the Compton chamber (a) and measured spot sizes (and position) of the electron beam (b) and the laser beam (c).

The light source consists of a pulsed neodymium-doped yttrium aluminum garnet (Nd∶YAG) laser, a beam expander, mirrors, and focusing lenses. The laser provides incident photons and the mirrors alter the optical path for the laser photons so that it collides with the electrons in the Compton chamber. The beam expander enlarges the laser beam so as to minimize the power loss. Moreover, the expanded laser beam is sequentially focused by the focusing lenses to increase the X-ray yield. The Nd∶YAG laser produces 17 ns (FWHM) output pulse of the wavelength of 1 064 nm (λ=1 064 nm, E_L=1.168 eV) with peak power of 10 MW at a repetition rate of 2.5 Hz. Interaction with a 107 MeV electron beam would generate an X-ray line at about 25 keV when the observation direction coincides with the electron beam direction. The Nd∶YAG laser beam is first expanded to a 20 mm diameter beam and then focused by a 17 cm focal lens. The lens focal point coincides with the center of the chamber, which focuses the laser onto the spot size of about 4 mm × 3.5 mm, as shown in Fig. 3(c). The collision angle between the laser-beam and electron beam was set to be about 40°. The generated X-rays from the LCS passed through a 200 μm thick beryllium window and traveled 10 m in air before reaching the detecting system.

The detecting system consisted of a lead collimator and a liquid nitrogen cooled high resolution Si(Li) detector. It was placed at 0° with respect to the beam line axis. The collimator was a hollowed cylinder with an inner diameter of 6 mm, an outer diameter of 84 mm, and was 60 mm long with a distance of 10 meters away from the end of the interaction region of the laser photons and the electron beams. After collimated, the generated X-rays were detected by the detector immediately behind the collimator. The solid angle subtended by the detector was about 0.28 μsr. The energy calibration and resolution of the Si(Li) detector was determined by calibrated radioactive sources of ^{55}Fe, ^{125}I, ^{238}Pu and ^{241}Am.

A pulsed Nd∶YAG laser for its high peak power caused the scattered photons to be periodically produced with the same frequency as the laser's repetition rate. The pulse length of laser was 17 ns, and taking into account the maximum interaction length (~5 m), the photons were produced within 34 ns for each laser pulse. However, the laser's repetition rate was 2.5 Hz. This observation would suggest that the photons were produced within a time period less than 8.5 ×10^{-6}% of the total counting time. For instance, 24 h total counting time implies that the photons were produced for only about 0.007s. Besides, the continuous noise bremsstrahlung (which was produced due to the interaction between electron beams and the residual gases as well as ions) was markedly higher than the scattered X-rays. Consequently, synchronously measuring the scattered photons became an extremely important task during the experiment.

Both of the laser system and DAQ were synchronized to the RF of the electron beam. Synchronization among the laser, electron beam and data measurement was achieved by sending three pre-trigger TTL signals. Two of them were used to control the laser flash lamp and Q-switch, respectively. The third provided the gate trigger signals and then allowed the detector's signals to pass through to the PC-based DAQ system.

3 Experimental Results and Discussions

The experiment was carried out at SINAP using the 1 ns, 107 MeV electron beam from the linear accelerator and the 17 ns, 10 MW peak power, pulsed Nd∶YAG laser.

In order to monitor the arrival time of the electron bunch and laser pulse at the interaction point, a wall-current monitor (WCM) and a PIN Junction Diode were used to provide signals from the electron beam and the laser pulse, respectively. The WCM was placed just after the Compton chamber and the PIN was located before the laser beam expander. The delay between the electron beam and laser pulses was measured and set to be 173 ns. One of them was displayed in Fig. 4. An approximate value of the jitter between the electron beam and laser was recorded. The jitter is of the order of 2 ns. This value of the jitter does not appear to be a severe limitation to observe LCS.

At the beginning of the experiment, the Si(Li) detector was placed on the e-beam axis approximately 1.8 m from the center of the interaction region. When the laser and electron beams are matched in focusing and synchronization, we tried to measure the produced X-ray spectrum and observe strong signals on the Si(Li) detector, most of signals were from the background (defined by high energy X-rays due to 107 MeV electron beam bremsstrahlung) and no clear LCS signals were detected.

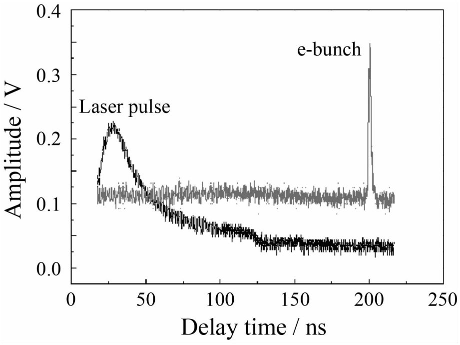

Fig. 4 Synchronization delay time between the electron beam and laser pulses.

In order to measure the produced X-ray spectrum, the count rate of the Si(Li)-detector should be limited to around 1 Hz. Several detector positions have been tested, and finally, the Si(Li) detector was fixed at the e-beam axis approximately 10 m from the center of the interaction region. Fig. 5 shows the LCS spectrum for the solid angle subtended by the detector was about 0.28 μsr. The spectrum was taken during different runs and the collection time for 1.83 h. It shows a clear sharp distinct monochromatic X-ray peak at (29±6) keV with net counts of 81±32 after background subtraction, but no X-rays are clearly visible in the measured spectrum owing to the fact that the background radiation from bremsstrahlung is extremely high. The collection time was 1.83 h during two different runs. A typical signal-to-noise ratio was as large as 410 at this detector position.

A 0.1 nC electron bunch contains 6.25 ×10^8 electrons. However, because the cross section of the e-beam is approximately double that of the laser's focus, only half of the total electrons in the bunch were scattered. Thus, we estimated that the average count rate for the electrons within the counter propagating laser pulse is around (0.003±0.001)/pulse.

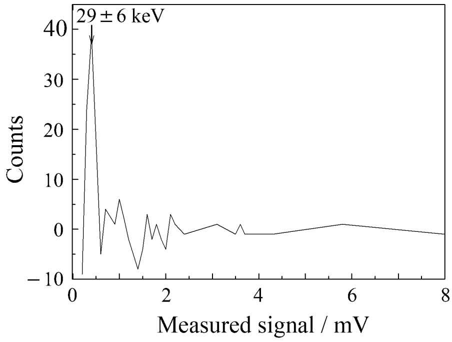

Fig. 5 LCS spectrum as measured by a Si(Li)-detector after background subtraction. An X-ray peak associated with 29±6 keV are clearly visible.

4 Summary and Outlook

The experiment to observe X-ray generation using Compton scattering of the relativistic electron beam of 107 MeV, 5 Hz, 1 ns, 0.1 nC electron bunches with the Nd∶YAG laser of 18 ns, 10 MW peak power has been carried out at the linear accelerator of SINAP. The Si(Li) detector, which was placed at the e-beam axis approximately 10 m from the interaction point, was used to measure the spectrum of the scattered X-rays. After background subtraction, a clear sharp distinct monochromatic X-ray peak at (29±6) keV with net counts of 81±32 has been observed in the 40° interaction geometry. In the near future, in order to improve the signal-to-noise ratio, a high-peak-power laser should be required, and the background radiation from bremsstrahlung needs to be reduced further.

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