Laser Compton scattering experiments and the latest developments in construction of experimental facilities at SINAP

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Abstract:
In this article, we report the two terms Laser Compton Scattering (LCS) via interaction experiments at 100 MeV linear accelerator of SINAP. The monochromatic X-rays were generated by a 108.1 MeV, 2.5 ns electron beam colliding with two Nd:YAG lasers of 113mJ/pulse, 35 ns and 2J/pulse, 10 ns, respectively, and demonstrate the latest developments in construction of experimental facilities at SINAP: a high-intensity ultrafast laser and electron interaction experimental facility based on Shanghai Deep Ultraviolet-Free Electron Laser (SDUV-FEL) device. In addition, we present a future Laser Compton Scattering (LCS) γ-ray source – Shanghai Laser Electron Gamma Source (SLEGS) at Shanghai Synchrotron Radiation Facility (SSRF) is presented. It is one of beamlines of SSRF in Phase II and will be finished around 2011.

Key words: Laser Compton Scattering (LCS); Shanghai Laser Electron Gamma Source (SLEGS); 100MeV & 150MeV Linac; Shanghai Synchrotron Radiation Facility (SSRF);

1. Introduction
Laser Compton Scattering (LCS) via interaction between high-power laser and electron beams can become a powerful tool not only for fundamental studies and new technologies, but also for the development of high-intensity, short-pulse, and compact X/γ-ray sources which is required for various fields of scientific, industrial, medical applications and so on. Developed detailed studies and applications include:
● Nuclear medicine application and γ/X-ray imaging technique [1, 2], including Compton Scattering Tomography, γ-ray transillumination imaging technique and so on.
● Cancer therapy by a γ-ray beam [3-5];
● Electron-positron pair creation from longitudinally polarized 56MeV γ-rays that are generated from Laser Compton Scattering [6];
● LCS γ-ray induced photo-transmutation [7, 8];
● Probing the structural dynamics of materials within femto-second intense X-ray pulses by Compton/Thomson Scattering [9, 10, 11];
● Electron beam diagnostics and its application by using LCS method in a storage ring or a linear accelerator [10, 12-17], including precision measurements of electron energy, divergence and spatial distribution of the electron density, and the measurements of electron polarization;
● Second-harmonic phenomenon [18, 19];
● Non-linear Compton Scattering effects [11, 12, 20-22];
In 2005, under the auspices of the Chinese Academy of Sciences Knowledge Innovation Program project, an experimental group at Shanghai Institute of Applied Physics (SINAP) was specifically organized to carry out a pulsed laser and electron beams collision experiment. Laser Compton Scattering experiments have been performed twice with two lasers and a 108.1MeV electron beam

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provided by the 100MeV linear accelerator of Shanghai Institute of Applied Physics in 2008. The monochromatic X-rays were generated by approximate 42° colliding a 108.1 MeV, 2.5 ns electron beam with two Nd:YAG lasers of 113mJ/pulse (SINAP I), 35 ns and 2J/pulse (SINAP II), 10 ns, respectively. We have shown that there is a good agreement between experiment data and theoretical predictions.

In the near future, Shanghai Deep Ultraviolet-Free Electron Laser (SDUV-FEL) facility is going to be constructed at Shanghai Institute of Applied Physics and finished within following two years. The synchronization between its laser and the electron bunch is expected to be about 100-fs. The electron bunch length will be 2-3ps (FWHM). It will make possible for us to further study the Laser Compton Scattering (SINAP III) in relativistic energy region with an updated terawatt laser based on this FEL device. Through SINAP III, we will therefore expect to observe nonlinear Laser Compton Scattering, to study laser acceleration of electrons and etc. In addition, Shanghai Laser Electron Gamma-ray Source (SLEGS) at Shanghai Institute of Applied Physics, as one of the phase II beam lines of Shanghai Synchrotron Radiation Facility (SSRF), will most likely begin to be constructed at the end of this year. SLEGS also utilizes Laser Compton Scattering via interaction between high-power laser and a 3.5GeV electron beam circulating in a storage ring of the SSRF. In this report, we will present details of the Laser-Compton Scattering programme and its latest developments at SINAP.

2. LCS X-ray source at SINAP

LCS X-ray source [23], as a prototype of SLEGS, has been installed at the terminal of a 100MeV linear accelerator (Linac) at the SINAP. Electron bunches within a 2.5 ns pulse width (FWHM) are generated at a 5 Hz repetition rate by the Linac. They are accelerated up to 108.1MeV by a 2856 MHz klystron and transported using bend magnets and quadrupoles to the interaction region inside the LCS chamber.

Figure 1 General arrangement 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 as electron source. A pulsed ND:YAG laser system was used for interaction with the electron beam. The repetition rates of e-bunch and laser pulse were 5 Hz and 2.5 Hz, respectively. This was synchronized to the RF of the electron beam, which was 2856MHz.

A general experimental arrangement is shown in Fig. 1. Using the four quadrupole magnets, the electron beam is focused at the center of the Compton chamber, where it is scattered against the laser beam. Some steering magnets combined with the quadrupole magnets are used to adjust the beam position. After a collision with the Nd: YAG laser at the interaction point (IP) (namely, the center of the vacuum Compton chamber) at the laser incident angle of 42° with respect to e-beam line axis, the e-beam is transported to a beam dump with the help of 30° bending magnet. The generated X-rays from LCS process pass through a 200 μm thick beryllium (Be) window and travel about 8 meters in air, and
finally are detected by an Si (Li) detector which is placed downstream Compton chamber. The distance between IP and X-ray spectrometer is 9.8 m, and the solid angle $\Omega$ subtended by the Si (Li) detector is about 0.28 $\mu$sr. On the left side of the LCS chamber in Fig. 1, a 30°-bending magnet deflected the electron beam onto a beam dump, away from the forward scattered X-rays. An absorption cell cooled by recycling distilled water is put outside of the Compton chamber and is used to absorb the un-scattered laser photons. The more details of first term experimental set-up and layout are shown in Ref. [24].

We did SLEGS prototype experiments twice using two lasers. Both lasers are Nd:YAG lasers but with a different peak powers and pulse widths. The main parameters of the used lasers and electron beam are listed in Table 1 and Table 2, respectively. In the two term LCS experiments in SINAP, the time jitters between Nd:YAG laser pulse and electron bunch at IP are measured to be 1.3ns and 1.0ns, respectively. They demonstrate that the two term experiments realize ns-ns order collision between laser pulse and electron bunch.

<table>
<thead>
<tr>
<th>Parameters of laser</th>
<th>First term (SINAP I)</th>
<th>Second term (SINAP II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>1064</td>
<td>1064</td>
</tr>
<tr>
<td>Peak power (MW)</td>
<td>$\leq$10</td>
<td>200</td>
</tr>
<tr>
<td>Pulse duration (ns)</td>
<td>35</td>
<td>8</td>
</tr>
<tr>
<td>Time jitter (ns)</td>
<td>$&lt;1$</td>
<td>0.6</td>
</tr>
<tr>
<td>Stabilization of power (%)</td>
<td>$&lt;5$</td>
<td>2–3</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

| Laser incident angle with respect to e-beam | $42^\circ \pm 2^\circ$ |

<table>
<thead>
<tr>
<th>Parameters of electron</th>
<th>First term</th>
<th>Second term*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (MeV)</td>
<td>108.1</td>
<td>108.1</td>
</tr>
<tr>
<td>Beam charge (nC)</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>Energy spread (‰)</td>
<td>$\sim$3</td>
<td>$\sim$3</td>
</tr>
<tr>
<td>Beam duration (ns)</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

$a^o$ is the difference between the measured value of angle and expectation value.
| *Parameters of electron beam in second term LCS experiment is the same as in first term experiment except the beam charges of electron bunch provided by 100MeV Linac. |

Because the signal to background ratio is quite small due to the bremsstrahlung background from the 100MeV electrons, the LCS process is designed to happen for every other electron pulse. Therefore one can extract the spectrum of the LCS X-ray by subtracting the spectrum with LCS process from the spectrum without LCS process. Owing to the above background subtraction method, the matched focusing, accurate alignment and synchronization of the Nd: YAG laser pulse and e-beam, the produced LCS X-ray spectrum has been observed in two experiments. The parameters of the obtained LCS X-rays by Si (Li) detector on two experiments are shown in Table 3.

When an incident laser photon strikes an electron of energy $E_e$ and velocity $\beta$ with a relative angle $\theta_L$, the energy of LCS X-ray in the plane of incidence (defined by the incident laser pulse and e-beam directions) is given by

$$E_x = \frac{E_L(1 - \beta \cos \theta_L)}{1 - \beta \cos \theta + \frac{E_L[1 - \cos(\theta_L - \theta)]}{E_e}}$$

(1)

Here $E_e$ and $E'_e$ are the kinetic energies of incident and scattered electron, $E_L$ and $E_x$ are the energies of incident laser photon and LCS X-ray. $\theta_L$ and $\theta$ are the incident angles of laser photon and scattered angle of LCS X-ray with respect to the direction of incident e-beam. From the Eq.1 we can get the peak region of LCS X-rays is 24.4 to 29.3keV when a 1064 nm Nd: YAG laser pulse Compton
scattered against a 108.1 MeV e-beam in 42°±2° configuration. The preliminary LCS X-ray peak energy and flux are listed in Table 3. The final experimental results of SINAP I and SINAP II will be published in other magazines. The preliminary results show reasonable agreement with the calculations.

Table 3 Summary of the parameters of the generated LCS X-rays on two experiments.

<table>
<thead>
<tr>
<th>SINAP I</th>
<th>SINAP II</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray peak (keV)</td>
<td>29.12±4.39±2.06</td>
</tr>
<tr>
<td>X-ray width (σ) (keV)</td>
<td>7.75±2.76±0.37</td>
</tr>
<tr>
<td>Signal-to-Noise (S/N)</td>
<td>1/406</td>
</tr>
<tr>
<td>Peak photon flux* (s⁻¹)</td>
<td>523±209</td>
</tr>
<tr>
<td>X-ray peak (keV)</td>
<td>31.73±0.23±1.64</td>
</tr>
<tr>
<td>X-ray width (σ) (keV)</td>
<td>0.74±0.26±0.03</td>
</tr>
<tr>
<td>S/N</td>
<td>1/780</td>
</tr>
</tbody>
</table>

*Normally 100MeV Linac operates with e-beam charge of 1.0nC/pulse and repetition of 20 Hz. In SINAP I, the measured X-ray flux is 0.012±0.005 s⁻¹. Our expectation photon flux is 0.011Hz. So it shows good agreement with each other.

3. High-intensity ultrafast laser and electron interaction experimental facility based on SDUV-FEL facility

Recently, a worldwide trend is to develop free electron device and its technique other than advanced third-generation synchrotron radiation light source because of a quantum jump of high-gain free electron theory and technique. The former has a characteristics of high peak brightness (ten orders higher than the latter), short-pulse (two or three orders short than the latter) and well-coherent. So it can open up a new way to study many subjects such as physics, biology. Several ultrafast, short wavelength and coherent free electron laser devices has been built or under construction, for example: SDL DUV-EFL in SDL/(NSLS), USA (since 2002), FLASH (TTF) in DESY, Germany (since 2006), SPARC in INFN Fraseati, Italy (in 2007), FERMI in Trieste, Italy (in 2009) and Euro XFEL in DESY, Germany (in 2014). In order to explore this kind of high-intensity and well-coherent photon source in China, SDUV-FEL facility is now under construction and its first term project will be accomplished in the end of 2009 at SINAP. SDUV-FEL works under the HGHG principle and contains three major parts: a high performance 160MeV linear accelerator, a 262nm HGHG undulator and a series of diagnosis system and time synchronization system of SDUV-FEL. The time synchronization of SDUV-FEL between its drive laser, seed laser and electron bunch is expected to be approximately 100-fs. The electron bunch length will be 2-3ps (FWHM). The 160 MeV Linac is now being upgraded by the above mentioned 100 MeV Linac such as photo-cathode rf gun and an accelerating section.

Based on the SDUV-FEL facility with high performance linear accelerator and good synchronization between laser and electron and developed two terms LCS experiments (SINAP I & SINAP II) successfully, both of them make possible for us to further study the Laser Compton Scattering (SINAP III) in relativistic energy region with an Ti: sapphire terawatt laser. The main parameters of a promising Ti: sapphire terawatt laser and the upgraded 160 MeV Linac are shown in Table 4.

Table 4 Main parameters of a preliminary Ti: sapphire terawatt laser and the upgraded 160 MeV Linac for high-intensity ultrafast laser and electron interaction experimental facility.

<table>
<thead>
<tr>
<th>160MeV linear accelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy(E) (GeV)</td>
</tr>
<tr>
<td>Beam intensity(I₀) (kA)</td>
</tr>
<tr>
<td>Normalized emittance (ε) (μm-rad)</td>
</tr>
<tr>
<td>Energy spread (σ₁/γ) (%)</td>
</tr>
<tr>
<td>Pulse duration(σₑₑ) (ps)</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
</tr>
<tr>
<td>Focused spot size (μm²)</td>
</tr>
<tr>
<td>High vacuum at Compton Chamber (Torr)</td>
</tr>
</tbody>
</table>

TW laser system
Laser type | Ti: sapphire
---|---
Wavelength (λ) (nm) | 80
Peak power (P₀) (TW) | 20
Pulse energy (J) | 0.6
Pulse duration (σₚ) (fs) | 30
Repetition rate (Hz) | 1~20
Polarization | Linear (on horizontal plane)
Focused spot size (μm²) | 50~100
Laser focused intensity (I₀) (W/cm²) | 4×10¹⁹

*a₀*: laser strength parameter is the normalized amplitude of the vector potential of the incident laser field and is related to the laser focused intensity I₀ and peak power P₀ of the incident laser by

\[ a₀ = \frac{\alpha A₀}{m c²} \]

From the Table 4 we can see that the laser strength parameter a₀ is larger than 1, which means the experimental facility of high-intensity ultrafast laser and electron interaction can become one of minority experimental facilities at relativistic optic region of photon field in which one can develop and employ LCS or nonlinear LCS experiment. Through SINAP III, we will get a hard X-ray source with a repetition rate of 10Hz, peak flux of 10⁶ to 10⁸/pulse and its energies region from several keV to several hundreds keV. In addition, we therefore expect to observe nonlinear Laser Compton Scattering, to study laser acceleration of electrons and radiation damping effect in high intensity ultrafast laser field, to check up and verify classical electrodynamics and nonlinear quantum electrodynamics theory and etc.

4. Shanghai Laser Electron Gamma-ray Source (SLEGS)

In order to meet the growing demand for synchrotron radiation application in China, the Chinese Academy of Sciences (CAS) and the Shanghai Municipal Government (SMG) made a joint proposal for constructing an advanced third generation synchrotron radiation light source, namely, SSRF [25, 26], and finally got approved in 1995. The energy of the electrons in the storage ring of the SSRF is 3.5GeV, which so far is the highest value of medium-energy light sources in the world. The SSRF contains four major parts: a 3.5GeV electron storage ring, a full energy booster, a 150MeV Linac, and an array of beamlines ranging from infrared light to hard x-rays. Macromolecular crystallography beamline (BL17U1) is one of the first seven beamlines and second commissioned in-vacuum undulator beamline development at the SSRF. It has been commissioned successfully in March 8, 2009 and is not only one but also the last one major milestone in developing the SSRF. It means the SSRF have accomplished all construction assignment as well since December 25, 2004. In the end of April, 2009, the SSRF will be received, inspected, and then be finished completely. Meanwhile, shanghai laser electron gamma source (SLEG)[27-31], as one of beamlines of SSRF in phase II, has been proposed and will be finished around 2011.

The aim of the project of SLEGS is the construction of a beamline at SSRF which extends the keV energy range of common synchrotron radiation sources into the MeV range and SLEGS will be one of the highest intensity beam lines of γ-ray at the SSRF. SLEGS is located at beamline BL20 – one of long straight sections of the SSRF storage ring. The entire facility consists of the BL20 front-end of the storage ring, a laser hutch, an experimental room, and a γ-ray beam dump. All of them are located outside the shielding wall at the SSRF. Fig. 2 presents the schematic diagram of the entire facility.
In order to obtain the features of the \(\gamma\)-ray generated from SLEGS from simulations, we have developed a C++ program using the Monte Carlo method to simulate the generation of the LCS \(\gamma\)-rays. Some important calculation and simulation results are presented in Ref [31]. And we also have seriously considered using commercial CO2 laser with 3.5GeV electron of SSRF to produce \(\gamma\) ray. It has several advantages comparing to others such as molecular gas lasers with longer wave lengths: 1) It is well developed, compact, and offers high quality; 2) High output power that promises a high flux of LCS \(\gamma\)-ray; 3) Run under both continuous and pulsed mode; 4) Relatively low cost and low technical risk; and 5) Easy to manage and control. Thus CO\(_2\) laser is the best option for SLEGS. The intrinsic wavelength of the CO\(_2\) laser is 10.64 \(\mu\)m and the corresponding photon energy \((E_\gamma)\) is 0.117 eV. Basic parameters of the CO\(_2\) laser which will be used in SLEGS are listed in Table 5.

Table 5 Basic parameters of the CO\(_2\) laser.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength ((\mu)m)</td>
<td>10.4~10.8</td>
</tr>
<tr>
<td>Peak power (MW)</td>
<td>500</td>
</tr>
<tr>
<td>Rise/fall time ((\mu)s)</td>
<td>&lt;90</td>
</tr>
<tr>
<td>Stabilization of power (%)</td>
<td>(\pm 8)</td>
</tr>
</tbody>
</table>

\(\gamma\)-ray with energies up to a few hundred MeV can be generated by Laser Compton backscattering of CO\(_2\) laser photons on the relativistic electrons circulating in the storage ring. If using 3.5 GeV, 200-300 mA relativistic electrons and a 500 W CO\(_2\) polarized laser, \(\gamma\)-ray intensities as high as \(10^7\)~\(10^8\)/s can be achieved without affecting the SSRF performance. The \(\gamma\)-ray beam will have a high degree of linear or circular polarization (80 - 100 %) with respect to the polarization direction of the incident laser beam. The simulation results show that an energy resolution of \(\gamma\)-ray of 1.5 % can be achieved by employing a proper collimator. In a word, the above shows that the SLEGS beam is a \(\gamma\)-ray source with a high, monochromatic intensity and a high degree of polarization. These beam characteristics can be used to explore many interesting field as well as the above LCS X-ray source [32]. The more details are shown partially in the Section of Introduction.

Conclusions

Laser Compton Scattering (LCS) via interaction is a useful tool to produce X/\(\gamma\)-ray source within good characteristic of high, monochromatic intensity, high degree of polarization, short-pulse and its generated X/\(\gamma\)-ray energies adjustable. This photon source is required to conduct a wide range of fundamental studies such as nuclear physics, particle physics, and astrophysics, and for various fields of scientific, industrial, medical applications and so on.

To date, we have demonstrated successful LCS experiments in the 42\(^\circ\) geometry using a 108.1 MeV, 2.5 ns electron beam interacting with two Nd:YAG lasers of 113mJ/pulse, 35 ns and 2J/pulse, 10 ns, respectively at SINAP, and observed X-ray energies and fluxes that agree well with the calculations. In addition, a brief introduction of a high-intensity ultrafast laser and electron interaction experimental facility based on SDUV-FEL and a future LCS \(\gamma\)-ray source at SSRF– SLEGS is presented.
Acknowledgments

The authors would like to express sincere thanks to the accelerator staff of the 100MeV Linac group at SINAP for operating 100MeV Linac. This work was supported in part by the following foundation items for their financial supports: One Hundred Person Project of Chinese Academy of Sciences (2006) (26010701); Knowledge Innovation Project of the Chinese Academy of Sciences (KJCX2-SW-N13); Pujiang Talent Project of the Shanghai Science and Technology Committee (06PJ14114); and the National Natural Science Foundation of China (10675156).

Reference:

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