An X-ray spectroscopy system and its application to the laser-Compton scattering experiments

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\textbf{A B S T R A C T}

One of the main challenges for the laser-Compton scattering (LCS) experiments with the oblique configuration at the Linac of SINAP is the low signal to noise (S/N) ratio due to the low intensity of LCS signals. X-ray spectroscopy system mainly consisting of an X-ray Si(Li) detector, electronics, and LabVIEW-based data acquisition has been developed for the low S/N ratio experiments. Spectral characteristics of such a system (i.e., energy and time resolutions, data acquisition efficiency, and system instability) have been determined by the \textsuperscript{55}Fe, \textsuperscript{241}Am, and \textsuperscript{238}Pu radioactive sources. In order to extract the LCS X-ray spectrum, several methods for the enhancement of the S/N ratio have been achieved and data have been taken alternatively with laser pulse on and off. Thanks to these methods the S/N ratios have been optimized. Finally, the generated LCS X-ray spectrum has been achieved through the subtraction of the on/off laser accumulated spectra.

\begin{center}
\includegraphics[width=\textwidth]{graph.png}
\end{center}

\textbf{1. Introduction}

Conventional X/\gamma-ray beams have found countless practical applications. There are many methods to generate X/\gamma-rays. Laser-Compton scattering (LCS) obtained through scattering of a high intensity electron beam and a high power laser beam is one of the most exciting methods used to generate X/\gamma-ray pulses [1,2]. Moreover, an LCS X/\gamma-ray source exhibits rather interesting behaviour like tunable photon energy, quasi-monomchromatic light, high flux, and low beam divergence [3]. For these reasons they have developed quickly in the recent decades. Such X/\gamma-ray source can be classified into either the Linac based [4–6] or electron storage ring based [7–9] accordingly to the types of the electron-accelerating facility. The proposed project named Shanghai laser electron gamma source (SLEGS), will be located at the 20th straight section of the Shanghai synchrotron radiation facility (SSRF) [10], and it will operate with a high intensity X-ray source in an energy range spanning from several MeV to hundreds MeV.

In order to address some technical issues concerning the construction of SLEGS, two terms proof-of-principle experiments [11,13] have been carried out recently at the Linac of Shanghai Institute of Applied Physics (SINAP). These experiments are based on Compton scattering measurements between the 1064 nm, 2.5 Hz, Nd:YAG laser pulses and \(~\sim\)108 MeV, 5 Hz electron macro-pulses. Since the energy-tunability for the future SLEGS is planned to be achieved by adjusting the collision angle between the laser beam and the electron beam, the collision angle for the present experiments is set at 40\degree. The generated X-ray energy is about 30 keV in agreement with the collision configuration.

In our LCS experiments, one of the main challenges is to detect and extract the generated X-rays because of the low signal to noise (S/N) ratio. Here we consider two main routes to enhance the S/N ratio. The first is to increase the signal yield. For example, we can use a higher power laser or assure that the size of laser beam is comparable to the size of the electron beam within the interaction volume. The second is reducing the backgrounds. In the present experiment the background radiation originates from two different mechanisms:

\begin{itemize}
  \item[i)] radioactive sources along the Linac tunnel produced by electron beam such as the electron beam dump, the beryllium window, and the accelerator tube wall, and
  \item[ii)] the pulsed bremsstrahlung, which is mainly produced by the interaction between the electron beam and the residual gases and ions inside the Linac.
\end{itemize}

For the suppression of the background radiations, a method of synchronous measurement gated with the electron macro-pulse has been designed and realized. A synchronous gate (40 \mu s) is
used to exclude most of the first type of the background radiation. However, the second type of the background radiation is produced spontaneously along with the generated X-rays, which therefore cannot be completely suppressed. Yet in offline data analysis we can still exclude more of the pulsed bremsstrahlung by using the coincidence information between the energy and time signals from the detector. In order to obtain the generated LCS X-rays from the remaining bremsstrahlung background, the LCS experimental data are alternatively recorded with laser pulse on and off. Therefore, the LCS X-ray spectrum is extracted through a subtraction of the accumulated laser-on and laser-off spectra. The details are reported in Section 3.

A careful design of the X-ray spectroscopy system is necessary in order to perform the LCS experiments. In the following the main points are summarized:

1) for measuring the 30 keV LCS X-ray signal, a silicon–lithium (Si(Li)) detector has been chosen since it is widely used for measuring X-rays with high efficiency and resolution in the energy range 0.5–60 keV;
2) for providing the synchronous gate, it is necessary to process time signal from the detector;
3) because the data are taken with a trigger frequency of 5 Hz, i.e. the repetition rate of the electron macro-pulse, the acquisition efficiency for the spectroscopy system needs to be about 100% at the count rate of 5 Hz;
4) because a continuous data collection is required during a few days from measurements of low intensity of LCS signal, the spectroscopy system needs to be stable; and
5) cost reduction is also desirable.

The aim of this work is to describe the setup of the X-ray spectroscopy system. The characteristics of this system are carefully tested and the results are reported in Section 2. The achieved methods for the enhancement of the S/N ratio, including the synchronous measurement for the background suppression, are presented in Section 3. The results of the two-term LCS experiments are also given in this section. Section 4 reports the conclusions of our experiment.

2. X-ray spectroscopy system and characteristics

The X-ray spectroscopy system eventually developed in our laboratory is based on the following main components:

i) X-ray Si(Li) detector with liquid nitrogen cooling and
ii) commercially available NI/PCI-6132 interface of simultaneous-sampling multi-function DAQ (4-Ch, 14-Bit, and 2.5 MS/s/ch).

A detailed layout of the system is shown in Fig. 1. We will give more details about these components and the relevant performances in the following.

2.1. Si(Li) detector and its carriage

The Si(Li) detector is designed and fabricated by Center of Advanced Instruments in our institute. A circular silicon–lithium drifted crystal with a thickness of 3.8 mm and a sensitive surface of 30 mm² is used for the fabrication of the Si(Li) detector. The crystal is kept in vacuum using a 7.5 μm beryllium window, while about 0.3 cm of air is set between the window and the Si(Li) detector crystal. A standard charge-sensitive pre-amplifier is used for the Si(Li) detector to detect both the charge and the time of occurring event. The charge-sensitive pre-amplifier is incorporated in a D-size shell box, while a 9-pin D connector is used as the port of power supply for the pre-amplifier. There are four separate connectors on the rear panel of the box: a fast-timing signal output channel, an energy signal output channel, a high voltage power supply connector, and a test input signal connector. The adjustment of the Si(Li) detector position is necessary for aligning precisely the Si(Li) detector with respect to the axis of electron beam line and measuring the X-ray yield as a function of...
the divergence angle. However, it is impossible to adjust Si(Li) detector position manually when the accelerator is operating for safety reasons. Therefore, a position-tunable detector carriage has been designed and built. Two stepper motors are mounted at the carriage and the vertical and horizontal positions of the Si(Li) detector are adjusted with a stepping precision of \( \pm 0.1 \) mm by operating the two stepper motors with a remote control.

### 2.2. Electronics and LabVIEW-based data acquisition system (DAQ)

The electronics readout of the Si(Li) detector is concerned with both the detector signal readout and the trigger system. A schematic diagram of the circuit system is shown in Fig. 1. Two signals from the pre-amplifier of the Si(Li) detector are transmitted to the data acquisition system. One of them is digitized with the charge ADC and stored on a disk as digital data. The other is used as the trigger and gate signals. The readout electronic system is composed of the standard ORTEC modules and National Instruments (NI) products. A NI/BNC-2110 connector and a NI/PCI-6132 interface card [14,15] have been developed to digitize signals and to record the digital data. For the control of the system and data collection, a PC is used in conjunction with a program written in LabView 7.1. A panel block of the developed LabVIEW-based DAQ software is shown in Fig. 2. This software can help to readin the pulse shapes, control the data acquisition process, and perform some data analysis. Then pulse peaks and shapes are recorded on a hard disk for offline analysis with ROOT toolkit.

### 2.3. Performance of the X-ray spectroscopy system

The LCS experiment employed an oblique interaction scheme (44°-configuration). This scheme has some advantages such as the energy tunability of the generated LCS X-rays [16], which is obtained by varying of the interaction angle. However, in this scheme the LCS X-ray yield was one or two order of its magnitude smaller than that of the backscattering configuration and thus the corresponding S/N ratio was smaller. Because of the long recording time required it was crucial to test carefully the spectroscopy system along with its stability. The characteristics of the spectroscopy system have been determined, including energy resolution (see Section 2.3.1 on Energy calibration), time resolution (see Section 2.3.2 on Time calibration), data acquisition

![X-Ray Spectrometer](image)

**Fig. 2.** An example of LabVIEW-based user interface. Controls are shown on the left side: pads (a) and (b) show an X-ray energy and time pulse shapes and (c) and (d) are the peak histogrammings with signals from energy channel and time channel, respectively.

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efficiency (see Section 2.3.3 on Acquisition efficiency of the DAQ software), and system stability (see Section 2.3.4 on System instability).

2.3.1. Energy calibration

$^{55}$Fe, $^{241}$Am, and $^{238}$Pu radioactive sources are used to calibrate this system. As an example, the measured X-ray spectrum of $^{55}$Fe is shown in Fig. 3(a). The energy calibration is displayed in Fig. 3(d), with a linear relationship between X-ray peak positions and their energies as follows

$$V = V_0 + aE$$

where $V$ represents the X-ray peak position in volt, $E$ is the X-ray energy in keV, and the parameters $V_0$ and $a$ are fitted to be $0.0071 \pm 0.0067$ V and $0.1019 \pm 0.0004$ V/keV, respectively. The energy resolution as full width at half maximum (FWHM) of the detection system is also measured to be 184 eV at 5.9 keV at the shaping time of 8 μs and input count rate of 1000 cps. The measured energy resolution of the Si(Li) detector is about 10% less than that of the ORTEC Si(Li) X-ray detector (Model SLP-06165P), but it can still meet the requirements of the present experiments and it is much less expensive.

2.3.2. Time calibration

Time calibration as well as the energy calibration is essential for X-ray detection. In fact it is useful for realizing the spectral characteristics of such a spectrometer, while also analyzing the time information of the generated photons. Here, we use an ORTEC model DB463 to adjust the delay between the pre-trigger TTL signal (the master trigger of the 100 MeV Linac) and the time signal from the Si(Li) detector. The calibration results are shown in Fig. 4. As an example, the time resolution of the spectroscopy system is found to be 0.56 at 63.5 ns with the range of 0.5 μs.

2.3.3. DAQ efficiency

The efficiency of the LabVIEW-based DAQ is defined as the ratio of the number of pulses recorded in the spectrum to the number of X-rays registered with the Si(Li) detector. Usually the NI/PCI-6132 operates with a sampling rate of 1.0–2.0 MHz (the maximum sampling rate is 2.5 MHz), and each pulse that flows into the DAQ software is then divided into 70 points, which

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**Fig. 3.** Measured X-ray spectra of radioactive sources: (a) $^{55}$Fe, (b) $^{238}$Pu, and (c) $^{241}$Am; (d) X-ray energy as a function of its peak position.

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correspond to 70 samplings per channel of the DAQ procedure. A scaler is used for recording the count rate of the detected X-rays by the Si(Li) detector \( (\text{RateScaler}) \). As a consequence, the DAQ efficiency \( (\xi) \) can be easily obtained by

\[
\xi = \frac{\text{Rate}_{70 \text{ samplings}}}{\text{RateScaler}} \times 100\%
\]

where \( \text{Rate}_{70 \text{ samplings}} \) represents the count rate recorded by the DAQ. Another method (i.e. continuous scan) for determining the acquisition efficiency is setting \( 10^6 \) samplings per channel when the sampling rate of the NI/PCI-6132 is 1 MHz, i.e., the DAQ card scanned for 1 s continuously. Once the ADC is triggered within the following 1 s, all X-ray signals would be recorded by the DAQ procedure. Correspondingly, the DAQ efficiency \( (\xi') \) can be obtained by

\[
\xi' = \frac{\text{Rate}_{70 \text{ samplings}}}{\text{Rate}_{10^6 \text{ samplings}}} \times 100\%
\]

where \( \text{Rate}_{10^6 \text{ samplings}} \) represents the X-ray count rate recorded in the scan process.

The DAQ efficiency is determined by the count rate up to \( 10^3 \) photons/s. Fig. 5 shows a plot of the two obtained efficiencies as a function of the count rate. One can see that both methods provide quite similar results reaching an efficiency better than 95% when the sampling rate is less than 20 Hz. During the LCS experiments, the LabVIEW-based DAQ records the data with a trigger frequency of 5 Hz. Therefore, it is possible to conclude that the measured DAQ efficiency can meet the requirement of the count rate for the LCS experiments.

### 2.3.4. Instability

The radioactive source \( ^{55}\text{Fe} \) is used to check the instability of the X-ray spectroscopy system; 323 data files in total have been recorded in seven days sequence measurements. The time interval between two close files is 0.5 h. Peak positions of 5.9 and 6.49 keV as a function of the measurement sequence are reported in Fig. 6. The energy jitter results to about 2 eV and the instability is about 0.3% for both 5.9 and 6.49 keV. The measured system instability shows that our spectroscopy system is reliable for the LCS measurement within a few days.

According to the characteristics of the X-ray spectroscopy system here reported, it is possible to note that the system is suitable to perform LCS experiments. However, because of the very low S/N, enhancing its improvement is mandatory. In the following the methods used for increasing the S/N ratio and performing the subtraction of backgrounds are reported.
3. Methods for enhancement of the $S/N$ ratio and subtraction of backgrounds

Two terms of the LCS experiments have been performed at the 100 MeV Linac of SINAP. X-rays with peak energy of about 30 keV are generated by interactions between electron macro-pulses (with energy of 108 MeV) and the Q-switched 1064 nm Nd:YAG laser pulses. Two different Nd:YAG lasers have been used for each term experiment. The pulse widths and pulse energies of the lasers are 21 ns and 0.113 J for the first term experiment, and 8 ns and 2 J for the second term experiment, respectively. During the LCS experiments, the repetition rates of the electron macro-pulse and laser pulse were 5 and 2.5 Hz, respectively. After passing through a 200 $\mu$m thick beryllium (Be) window, a 7 mm width lead slit, and 7.8 m air, the generated LCS X-rays reach the Si(Li) detector placed along electron beam line (the solid angle subtended by the Si(Li) detector was 0.29 $m^2sr$). As a result, the LCS X-ray signal is generated as the detector detects the generated LCS X-rays.

In order to distinguish the signal, two methods for the enhancement of the $S/N$ ratio through the background suppression have been used. At first, a synchronous measurement is achieved by setting an ADC gate (40 $\mu$s) with the frequency of the electron macro-pulse's repetition rate (5 Hz). The process of the synchronous measurement is illustrated in Fig. 7. Synchronization between the electron macro-pulse and laser pulse can be achieved by sending three TTL signals from a master (TTL pulse generator) spontaneously. Two of them are for triggering the electron gun and the Q-switch of the laser. The third TTL signal is fanned out into two. One signal is used as the start signal of the TAC. The other signal is used as the synchronous gate signal (40 $\mu$s) for the DAQ to allow the energy and time signals from the detector to pass through to the PC-based data acquisition system. As a result, most of the background radiations except the pulsed bremsstrahlung are excluded by the synchronous gate.

Then, a software time cut/gate is set for the offline data analysis. The measured data of our second term experiment are shown in Fig. 8. The events displayed of energy deposition in the Si(Li) detector versus the time (see Fig. 8(c) and (d)) can be clearly separated into three parts: the LCS X-rays as well as the background radiations with low energy at the time channel near zero (due to the time channel threshold of $\sim 150$ mV), the bremsstrahlung radiation with the energy above the electronic threshold (the slide band shown in Fig. 8(c)), and the overflow signals of the bremsstrahlung whose amplitudes are larger than the range (10 V) of ADC (the straight band around the time channel of 5.4 V shown in Fig. 8(c)). Clearly, these results show that it is possible to use a software time cut/gate of $\sim 300$ ns for the first part of the data to further exclude some of the pulsed bremsstrahlung radiations and extract the effective LCS X-ray signals. In fact, the $S/N$ ratios for both the experiments are increased by a factor of about two.

For subtracting the rest of the backgrounds, the LCS experimental data are taken alternatively with laser pulse on and off. The generated LCS X-ray spectrum is obtained through the subtraction of two accumulated spectra of laser pulse on and off. A similar method has been widely used for the high precision measurement of spin asymmetry [17]. By fitting the subtracted LCS X-ray energy spectrum, the peak energies and the peak widths of the LCS X-rays are obtained in two terms of LCS experiments, SINAP I and SINAP II. Table 1 shows the parameters used for our two terms of LCS experiments together with the results obtained for the generated LCS X-rays. The measured peak energies are consistent with each other for the two experiments.

4. Summary

A reliable X-ray spectroscopy system consisting of a Si(Li) detector, commercially available electronics, and LabVIEW-based DAQ has been developed in SINAP. The specific characteristics of such spectrometer, i.e., energy and time resolutions, calibrations, data acquisition efficiency, and system instability are measured and analyzed using $^{55}$Fe, $^{241}$Am, and $^{238}$Pu radioactive sources. The energy resolution (FWHM) and the energy instability of the system are obtained to be 184 and 2 eV, respectively, at 5.9 keV. The time resolution is determined to be 0.56 at 63.5 ns within a range of 0.5 $\mu$s. The system efficiency is measured with a count rate up to 3 kHz resulting close to 100% when the count rate is less than 10 cps.

Afterward, the X-ray spectroscopy system has been used to characterize the generated LCS X-rays. By setting suitable methods for enhancing the $S/N$ ratio the generated LCS X-ray spectrum can be extracted through the subtraction of two accumulated spectra of on and off laser pulses.

![Fig. 7. Process of synchronous measurement.](image-url)
Acknowledgements

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Table 1

<table>
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<tbody>
<tr>
<td>Electron beam</td>
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<tr>
<td>Macropulse energy (MeV)</td>
<td>108</td>
<td>112</td>
</tr>
<tr>
<td>Macropulse charge (nC)</td>
<td>~0.1 (1.0)</td>
<td>0.027 (1.0)</td>
</tr>
<tr>
<td>Pulse length, rms (ns)</td>
<td>0.95</td>
<td>0.9</td>
</tr>
<tr>
<td>rms spot size at focus, (\sigma_x/\sigma_y) (mm)</td>
<td>3.1/2.5</td>
<td>1.5/1.9</td>
</tr>
<tr>
<td>Nd:YAG laser</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wavelength (nm)</td>
<td>1064</td>
<td>1064</td>
</tr>
<tr>
<td>Pulse energy (J)</td>
<td>0.113</td>
<td>0.9 (2.0)</td>
</tr>
<tr>
<td>Pulse duration FWHM (ns)</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>rms spot size at focus, (\sigma_x/\sigma_y) (mm)</td>
<td>&lt;0.5/0.5</td>
<td>&lt;0.2/0.2</td>
</tr>
<tr>
<td>Laser incident angle</td>
<td>42° ± 2°</td>
<td>44° ± 2°</td>
</tr>
<tr>
<td>Relative time jitter at interaction point (ns)</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Peak energy (keV)</td>
<td>29.1 ± 4.4(\text{stat}) ± 2.1(\text{syst})</td>
<td>31.73 ± 0.22(\text{stat}) ± 1.64(\text{syst})</td>
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<tr>
<td>Peak width (keV)</td>
<td>7.8 ± 2.8(\text{stat}) ± 0.4(\text{syst})</td>
<td>0.74 ± 0.26(\text{stat}) ± 0.03(\text{syst})</td>
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Fig. 8. Measured energy and time spectra by the X-ray spectroscopy system: (a) and (b) are energy spectrum and time spectrum and (c) and (d) are 2D- and 3D- plots of energy deposition in the Si(Li) detector against the time, respectively.

References


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