ENERGY MEASUREMENT OF RELATIVISTIC ELECTRON BEAMS BY LASER COMPTON SCATTERING

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ABSTRACT

Laser Compton scattering by relativistic electrons provides the energy information associated with electron beams in an accelerator. Determining the electron beam energy by this method depends primarily on the signal to noise (*S/N*) ratio associated with laser Compton scattering. In this study, we propose a method to enhance the S/N ratio by synchronous measurement with a high peak power pulsed CO_2 laser. In this method, the pulsed CO_2 laser provides the gate trigger signals, and the delay times of the triggers are optimized to obtain a maximum *S/N* ratio. In the storage ring of Taiwan Light Source, a γ-ray with the highest energy of *3.021MeV* was back-scattered after the *0.1172eV* CO_2 laser photons colliding with the relativistic electrons. The *S/N* ratio is around *42.5* with the electron beam current being *19mA*. Also, the measured electron beam energy is *1.3058GeV* with relative uncertainty of *0.13%*.

1. INTRODUCTION

Compton scattering of photons by free electrons is a simple quantum-electrodynamics process that is experimentally accessible. Since A. H. Compton[1] presented the first semi-quantum-mechanical treatment of such an interaction in 1922, many theoretical calculations of the characteristics of Compton scattering have been developed.

Two conventional approaches of measuring the electron beam energy are to measure the depolarization resonance and measure the magnetic field strength of the bending magnets. The depolarization resonance[2] method has the smallest relative energy uncertainty, e.g., 10^{-5}; however, this method involves the complexity of measuring the electron beam polarization. The relative energy uncertainty of measuring the magnetic field strength is around the order of *0.5%*.

In this study, we propose a method capable of providing an intermediate relative energy uncertainty with an easier measurement setup than that of the depolarization resonance method. Here the electron beam energy is measured by using laser Compton scattering. The method can be applied to any high energy ($\gamma \gg 1$) electron beam. The experiment is performed on the electron beam in the storage ring of Taiwan Light Source (TLS) of Synchrotron Radiation Research Center (SRRC), Taiwan. The techniques include aligning and focusing for far infrared, synchronously measuring the back-scattered photons, and reducing background radiation from Brems-strahlung.

To acquire a high γ-ray flux, a pulsed CO_2 laser with up to *2.67MW* peak power is employed. Owing to the fact that the background radiation from Brems-strahlung is extremely high (about *1200counts/sec* at *20mA* electron beam current) and the time duration for γ-rays to be produced is quite short (less than *60ns* per pulse), how to effectively subtract the background radiation is a relevant concern. In this study, we develop the method of synchronous measurement to resolve the above problem. The method proposed herein increases the signal to noise ratio from *1.2* to *42.5*. Also, to enhance the collision rate, we develop a simulation program to optimize the optics system. The relative energy measurement error of this experiment is *0.13%*.

The techniques of laser Compton scattering developed in this study will contribute toward the development of tunable X-ray sources and that of a future FEL (Free Electron Laser) facility in the booster of TLS. The tunable wavelengths enable the tunable X-ray sources and the FEL to be highly effective tools in many applications such as medical image recording, nuclear physics research, and industry.

2. THEORY

Feenberg and Primakoff[3] first proposed the kinematics formulas for Compton scattering on moving electrons in 1948. Suppose that the laser photon and the electron approach each other at some relative angle θ_1. After back-scattering, the γ-ray emerges at a small angle θ_2 relative to the electron′s direction. The γ-ray energy is then given by

$$E_\gamma = \frac{E_L(1-\beta\cos\theta_1)}{(1-\beta\cos\theta_2)+\dfrac{E_L(1-\cos\chi)}{E_e}} \tag{1}$$

where E_L is the incident laser photon energy, E_e is the incident electron energy, $\chi=\theta_2-\theta_1$, $\beta=v/c$ with v and c the velocities of the electron and light.

3. ERROR ESTIMATIONS

Using the error propagation method at the highest back-scattered photon energy E_s, one can derive the relative electron beam energy measuring error, ΔE_m, as[4]

$$\frac{\Delta E_m}{E_e} = \frac{1}{2}\sqrt{(\frac{\Delta E_s}{E_s})^2 + (\frac{\Delta E_L}{E_L})^2} \tag{2}$$

where $\Delta E_s/E_s$ is the relative back-scattered photon energy measuring error,

$$\frac{\Delta E_s}{E_s} = \sqrt{(\frac{\Delta E_L}{E_L})^2 + (\frac{2\Delta E_e}{E_e})^2 + (\frac{FWHM/2.35}{E_s})^2} \qquad (3)$$

with $\Delta E_L/E_L$ and $\Delta E_e/E_e$ being the relative energy deviations of the laser photons and the electron beam, respectively. The last term, i.e., *FWHM/2.35*, represents the detector′s energy resolution.

Suppose that the electron beam energy E_e*=1.3GeV*, ΔE_e*=0.86MeV*, the *FWHM* at *3.021MeV* is *10keV*, and $\Delta E_L/E_L$*=0.001*, then the corresponding relative energy measuring error is about *0.24%* for the back-scattered photons and about *0.12%* in determining the electron beam energy.

4. EXPERIMENTAL DESIGN

The experiment was performed at the fourth straight section of the storage ring (R4A1 section) of Taiwan Light Source. The entire system consisted of the optical system, the detecting system, and the signal processing instruments. Fig. 1 demonstrates the entire system′s schematic diagram. According to this figure, the laser photons pass through the optical system into the storage ring′s straight section. After being scattered by relativistic electrons, the γ-rays pass through the lead collimator and are then detected by the HPGe detector. Later, the signal processing instruments acquire the back-scattered γ-rays(spectrum.

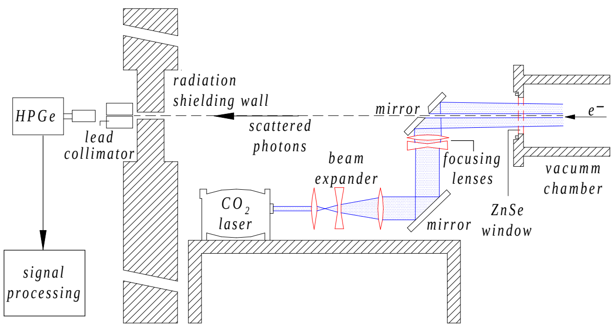

FIG. 1 Schematic diagram of the overall system: part of the vacuum chamber of the storage ring, optical system, detecting system, and signal processing system.

The optical system consists of a pulsed CO_2 laser, a beam expander, mirrors, and focusing lenses. After scattered by the laser photons, the electrons are bent by the bending magnets toward the storage ring′s next section, while the laser photons are scattered backwards. The upper mirror is hollowed out for the back-scattered photons to pass through to the HPGe detector along the incident photons(path. The beam expander enlargers the laser beam so as to minimize the power loss due to the hole on the upper mirror. Moreover, the expanded laser beam is sequentially focused by the focusing lenses to increase the back-scattered photon yield.

The detecting system consisted of a lead collimator and an HPGe detector. The collimator was a hollowed cylinder with an inner diameter of *3mm*, an outer diameter of *100mm* and was *100mm* long with a distance of *669.5cm* away from the end of the interaction region of the laser photons and the electron beams. After collimated, the back-scattered γ-rays were detected by the portable HPGe detector immediately behind the collimator.

Considering that the highest energy of the back-scattered photons was around *3000keV*, we chose ^{24}Na the standard source in energy calibration of the HPGe detector since the two characteristic energies of ^{24}Na were *1368.4keV* and *2753.6keV*. Those energies contributed to a sum-peak energy of *4122keV* which could be applied to the interpolation method in energy calibration.

5. SYNCHRONOUS MEASUREMENT

Using a pulsed CO_2 laser for its high peak power caused the scattered photons to be periodically produced with the same frequency as the CO_2 laser′s repetition rate. The pulse length of CO_2 laser was *30ns*, and taking into account the maximum interaction length (*10m*), the photons were produced within *60ns* for each laser pulse. However, the CO_2 laser′s repetition rate was at most *200Hz*. This observation would suggest that the photons were produced within a time period less than $1.2\times10^{-3}\%$ of the total counting time. 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 back-scattered photons. Consequently, synchronously measuring the back-scattered photons became an extremely important task.

The synchronous measurement used a gate (which is triggered by the CO_2 laser‘s trigger output) to periodically allow the signals to pass from the detector to the counting system. Fig. 2 illustrates the experimental setup of synchronous measurement.

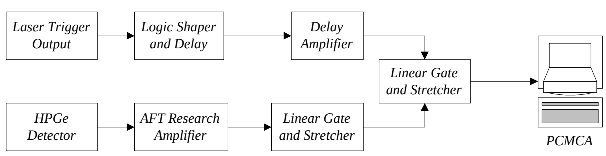

FIG. 2 Instruments associated with synchronous measurement.

6. EXPERIMENTAL RESULTS

Figures 3 to 5 display the spectra of the back-scattered γ-rays. Fig. 3 presents the spectrum of the Compton scattering with a collimator having an inner diameter of *3mm* which corresponded to a half opening angle of *0.2241mrad*. The background radiation′s counting rate without the laser Compton scattering effect was around *0.82 counts/sec*. After the laser photons collided with the electron beams, the counting rate raised to around *34.83 counts/sec*, i.e., the *S/N* ratio was approximately *42.5*.

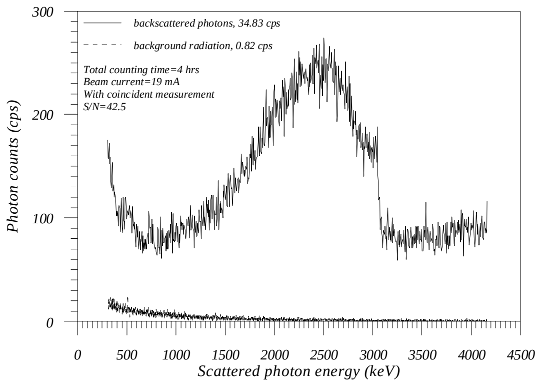

FIG. 3 γ-ray spectrum of Compton scattering with collimator of *3mm* diameter under synchronous measurement. (electron beam current=*19mA*, counting time=*4hrs.*, and *S/N* ratio =*42.5*.)

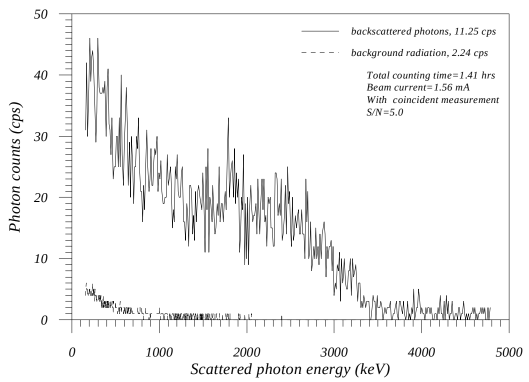

FIG. 4 γ-ray spectrum of Compton scattering with collimator of *10mm* diameter under synchronous measurement. (electron beam current=*1.56mA,* counting time=*1.41hrs.*, and *S/N* ratio =*5.0*.)

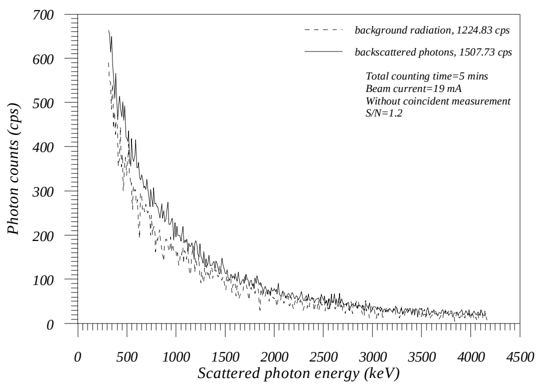

FIG. 5 γ-ray spectrum of Compton scattering with collimator of *3mm* diameter and without synchronous measurement. (electron beam current=*19mA*, counting time=*5mins.*, and *S/N* ratio =*1.2*.)

Figures 4 and 5 demonstrate the importance of the collimator′s size, and the synchronous measurement. Fig. 4 presents the spectrum of the Compton scattering with a collimator having an inner diameter of *10mm* which corresponded to a half opening angle of *0.818mrad*. The electron beam current was *1.56mA* and, in this case, the *S/N* ratio was *5.0*.

Figure 5 shows the spectrum obtained under the same conditions as in Fig. 3, but without synchronous measurement. In this case, the *S/N* ratio was only about *1.2*. Comparing the two spectra reveals the significance of synchronous measurement. Apparently, the synchronous measurement could significantly enhance the *S/N* ratio.

From Fig. 3 We can estimate the back-scattered photon energy corresponding to the central energy of the electron beam at the middle point of the sharp edge. Through some data processing, this photon energy can be derived as *3054keV* with a standard deviation of *2.6keV*. According to Eq. (1), the electron beam′s central energy can be expressed as

$$\gamma = \frac{\frac{4E_L E_\gamma}{m_0 c^2} + \sqrt{(\frac{4E_L E_\gamma}{m_0 c^2})^2 + 16 E_L E_\gamma}}{8E_L} \quad (4)$$

Offering E_γ=*3054keV*, we obtain *γ=2555.4* corresponding to the electron energy *1.3058GeV*, which is consistent with the results obtained from beam dynamics study[5] by the beam dynamics group of SRRC. In addition, our measured relative error for the electron beam energy is *0.13%*.

7. CONCLUSIONS

The synchronous measurement that contributes to a higher *S/N* ratio is the primary design feature of the laser Compton scattering experiment. This method employed the laser trigger outputs to trigger the gate. After the optimization process, a maximum *S/N* ratio was achieved at *42.5*.

Since the back-scattered photon energies were strongly angular dependent, precisely aligning the collimator and the optical system was deemed essential. The highest back-scattered γ-ray energy could be estimated from the sharp edge of the spectrum as shown in Fig. 3. For our latest experiment, it was *3054keV±2.6keV*. According to the results, we can infer that the electron beam energy was *1.3058GeV ±0.0017GeV*.

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