Design Study of Laser Compton Scattering with Relativistic Electron to Measure the Electron Beam Energy

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Abstract

This paper presents the design study of a system to measure the electron beam energy in an accelerator. The method of Compton scattering between laser photons and relativistic electrons was used. The optical system for the laser light was design to match the laser beam with the electron beam in order to enhance the back scattered photon flux. A simulation program was developed to study the effects of the beam energy spread and the beam divergence on the backscattered photon spectrum. A CO_2 laser was chosen to produce 3.03 MeV back scattered photons that will be detected with a high purity germanium detector(HPGe). The calibration of the detector at the energy of 3 MeV will be discussed.

I. INTRODUCTION

Compton back scattering of the laser light from relativistic electrons can produce quasi-monochromatic photon beam. The energetic photon beam, as a γ-ray source or X-ray source, can be used for the investigation of photonuclear reaction, the calibration of the detectors, medical image, and electron beam diagnostics[1] Here we use this method to measure the electron beam energy.

By measuring the back scattered photon energy, the electron beam energy can be deduced from that. There are several important issues have to be considered carefully in order to make this method be feasible. They are photon yield, detector efficiency, detector energy calibration, detector energy resolution and other effects which may affect the final photon counting rate and the measurement errors. The photon yield and detector efficiency has been studied in a previous paper[2]. The other issues was discussed in the following sections.

II. THEORY

The kinematics associated with the scattering is discussed by many papers. The process is shown in Fig. 1. The scattered photon energy k_2 from laser photons of energy k_1 in lab. frame is[3]

$$k_2 = \frac{k_1(1-\beta\cos\theta_1)}{1-\beta\cos\theta_2 + k_1(1-\cos\chi)/E_e} \qquad non-head-on \qquad (1.1)$$

or

$$k_2 = \frac{4\gamma^2 k_1}{1+\frac{4\gamma k_1}{mc^2}+\gamma^2\theta^2} \qquad head-on \qquad (1.2)$$

where $\chi = \theta_2-\theta_1$, $\beta = v/c$ with v and c the velocities of the electron and the laser light, θ is the angle between the laser and the scattered photons, and E_e is the electron energy.

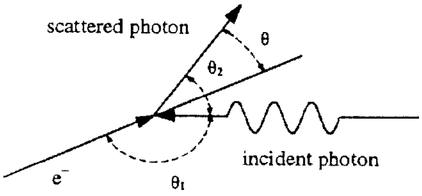

Fig. 1 The schematic drawing of the process of Compton scattering

The Klein-Nishina formula shows the differential cross section $d\sigma$ for the head on collision in the electron rest frame. For the lab. frame, after the Lorentz transformation, it is rewritten as[4]

$$d\sigma = \frac{\pi r_0^2}{2}\frac{m^2}{k_1E_e^2}[\frac{m^4}{4k_1^2E_e^2}(\frac{k_2}{E_e-k_2})^2 - \frac{m^2}{k_1-E_e}(\frac{k_2}{Ee-k_2})+ \frac{E_e-k_2}{E_e}+\frac{E_e}{E_e-k_2}]dk_2 \qquad (2)$$

where r_0 is the classical electron radius, and m is the electron rest mass. The photon yield Y per pulse is given by

$$Y = \frac{2N_eN_p\sigma d}{A\tau} \qquad (3)$$

where N_e and N_p are the number of electrons and laser photons per pulse, d is the average interaction length, A is the larger one of the transverse beam size of the electron beam and the laser beam, and τ is the longer one of the pulse length of the electron beam and the laser beam. σ is the total cross section of photons and electrons.

III. SYSTEM DESIGN

The system was designed to induce the Compton scattering effect and to measure the back scattered photon energy. A pulsed CO_2 laser with high peak power was chosen to produce the back scattered photons with maximum energy 3.03MeV. The schematic drawing of the whole system was shown in Fig. 2.

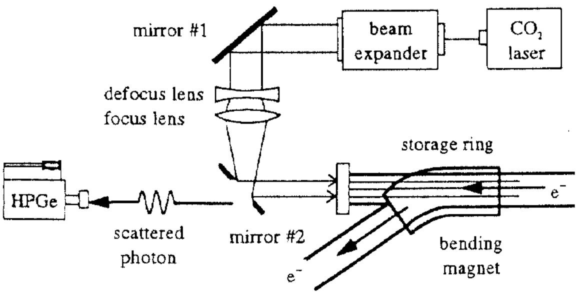

Fig. 2 The designed experimental setup

A . Detector Energy Calibration

In the following of this section, we will discuss another important issue – detector energy calibration. Since the maximum energy of the Compton scattered photon is as high as 3.02MeV, it would be unrealistic if we use the standard radiation sources such as ^{60}Co and ^{137}Cs to do energy calibration through extrapolation method. In our case, we have to find another radiation source with its gamma ray energy close to 3.02MeV. So far we have developed three methods to serve the purpose:

1. Neutron activation of ^{48}Ca with the gamma decay energy of ^{49}Ca is 3084keV. This method, however, suffers from the difficulty of establishing the gamma spectrum of ^{49}Ca due to the impurity ^{23}Na which has a longer lifetime than that of ^{49}Ca after it was activated to ^{24}Na. This can be partially solved by choosing a high purity specimen of ^{48}Ca or by reducing the neutron irradiation time to decrease the relative effect of ^{24}Na .
2. .Prompt gamma experiment. In this experiment, we use ^{252}Cf as neutron source to activate Si. The activated Si will then release prompt gamma rays with its gamma spectrum containing two peaks at 3539.1keV and 4934.4keV respectively. The single escape peak behind the 3539.1keV peak is about 3028.1keV which is then used as the reference in energy calibration (Fig.3).

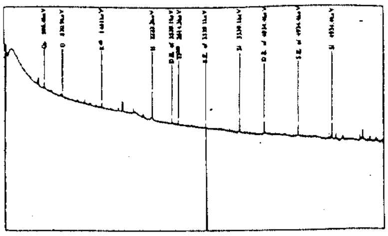

Fig.3. spectrum of the prompt gamma of earth

3. The previous two methods may give a certain amount of radiation dose to the operators. For the sake of radiation protection, we may want to find an easy way to reduce the dose that operators will get. This is done by the detection of the radiation of ^{208}Tl in earth. The gamma spectrum of ^{208}Tl has two peaks at 583.2keV and 2614.3keV respectively. If photons of such two peak energies come into the detector within its resolving time, then the detector will treat these photons as if they had only one photon with energy 3197.5keV, i.e., the sum of the two peak energies. Since the amount of ^{208}Tl in earth is not sufficient to get a clear 3197.5keV peak , We must increase our detection time or use NBS-4353 standard earth specimen as the source (Fig. 4)

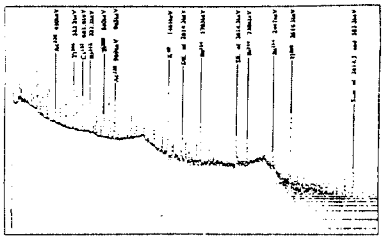

Fig. 4 Gamma spectrum of NBS-4353 standard earth

B. Error Analysis

In our study, we took the effects of the electron beam energy spread ΔE_e, the line broadening of CO2 laser Δk_1, and the resolution of HPGe, *Res*, into account to estimate the back scattered photon energy spread Δk_2 by the square root sum :

$$\frac{\Delta k_2}{k_2} = \sqrt{(\frac{2\Delta E_e}{E_e})^2 + (\frac{\Delta k_1}{k_1})^2 + (\frac{\sigma_d}{k_2})^2} \qquad (9)$$

where $\sigma_d = Res/2.35$. The calculated value of the back scattered photon energy spread at 3.03 MeV is 0.4%. The energy uncertainty of the 1.3 GeV electron beam will be 0.2%, if we used the energy resolution of HPGe at 3MeV as 3.27 keV.

IV. COMPUTER SIMULATION

As we do computer simulation to predict the spectrum of the scattered photons, We suppose the photons are monochromatic while the incident electrons are of variant energies and angles. Through twice Lorentz transformations we get the energies of the back scattered photons, which are then processed by the MCA subroutine to get the spectrum. From the simulation, we got the following results:

1. For the case of head-on collisions between photons and monoenergetic electrons, when agree with will analytic results. The spectrum was shown in Fig. 5.
2. For non-head-on collisions between photons and monoenergetic electrons with Gaussian distributed incident angles (beam divergence), the spectrum was shown in Fig.6. In this case, we found that the number of the photons with maximum energy decreases due to the beam divergence. It causes the sharpness of the spectrum

at maximum energy to be duller than that of the case of head-on collision. It can be seen that, however, the energy spectrum of the scattered photons is hardly affected by the beam divergence.

3. Taking the finite energy resolution of the detector into consideration, we find that since the HPGe detector has a relatively high energy resolution, it has little effect on the energy spectrum of the scattered photons (Fig. 7).
4. For the case of head-on collision between photons and the electrons with energy distribution being Gaussian, we find that the broader the energy distribution is , the larger the energy deviation of the scattered photons would be. This can be seen from the broadening of the spectrum at the high energy part(Fig. 8).

V. DISCUSSION

During these studies, we simplified the whole processes. The above results are under the following assumptions :

1. The electron beam moves in the center of the orbit.
2. The alignment of the laser beam to the electron beam was well done.
3. Beam size effect is about the same as that of beam divergence.

The standard source for energy calibration in the experiment we chose is the prompt gamma of Si. From the results of computer simulation we got the factors that would affect the photon energy measurement to be (1) energy spread of the electron beam, (2) resolution of the detector and (3) the energy spread of the laser photons. It was showed that the energy spread of the electron beam played the most important role in energy measurement while the energy spread of the photons was of least importance. Also it was showed that the beam divergence of the electron beam only affected the photon number at maximum energy.

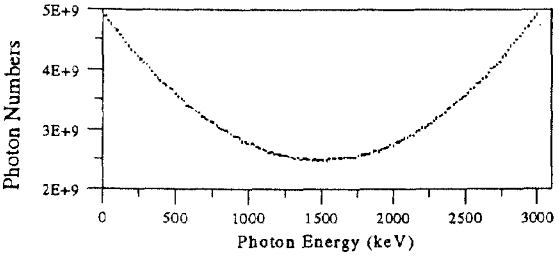

Fig. 5. Head-on collision before going into the detector

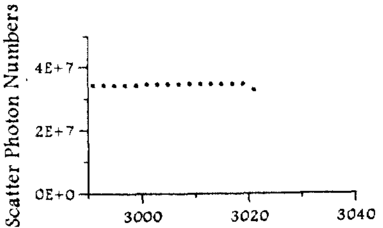

Fig. 6. Spectrum of non-head-on collision for monoenergetic electrons with beam divergence (high energy part)

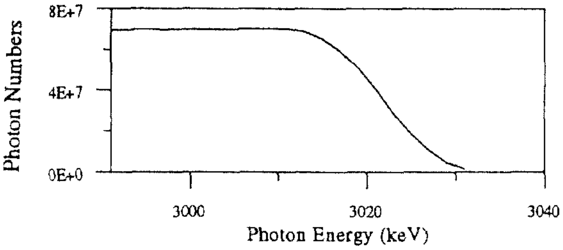

Fig. 7. Spectrum of head-on collision through detector (high energy part)

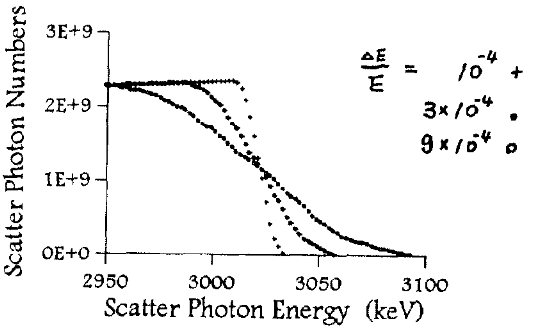

Fig. 8. Spectrums for head-on collision with different energy spread of electron beam

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