© 1993 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

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

Ian Hsu, Hone-Cheng Chen, Chen-Lien Cho, and Yuen-Chung Liu#

Institute of Nuclear Science, National Tsing-Hua University and Synchrotron Radiation Research Center Hsinchu, Taiwan 30043, R.O.C.

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. By knowing the back scattered photon energy, the electron beam energy can be deduced. The scattering mechanism between the laser photons and the relativistic electrons was well known. The optical system for the laser light was design to match the laser beam with the electron beam in order to enhance the backscattered photon flux. The implementation of the system in the electron beam transport line in SRRC and the optimization method will be discussed. A CO₂ laser was chosen to produce 3 MeV backscattered photons that will be detected with a high purity germanium detector(HPGe). The reason of using HPGe and the predicted results will be presented. Under this study, a 0.5 % energy measurement accuracy was expected.

I. INTRODUCTION

Compton backscattering of the laser light from relativistic electrons can produce quasi-monochromatic photon beam. The energetic photon beam can be used for the investigation of photonuclear reaction, the calibration of the detectors, and electron beam diagnostics^[1]. Here we use the method of Compton scattering and design a system to measure the electron beam energy.

II. THEORY

The kinematics associated with the scattering is discussed by many papers. The process is shown in fig.1.



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

The scattered photon energy k_2 from laser photons of energy k_1 in lab. frame is ^[2]

$$k_2 = \frac{k_1(1 - \beta \cos \theta_1)}{1 - \beta \cos \theta_2 + k_1(1 - \cos \chi)/E_{\epsilon}}$$
(1)

and can also be expressed as

$$k_2 = \frac{4\gamma^2 k_1}{1 + \frac{4\gamma k_1}{1 - \frac{2}{\gamma^2} + \gamma^2 \theta^2}}$$
(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. The Klein-Nishina formula shows the differential cross section d σ for the head on collision, after the Lorentz transformation, is rewritten as ^[3]

$$d\sigma = \frac{\pi r_0^2}{2} \frac{m^2}{k_1 E_e^2} \left[\frac{m^4}{4k_1^2 E_e^2} (\frac{k_2}{E_e - k_2})^2 - \frac{m^2}{k_1 E_e} (\frac{k_2}{E_e - k_2}) + \frac{E_e - k_2}{E_e} + \frac{E_e}{E_e - k_2} \right] dk_2$$
(3)

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

$$Y = \frac{2N_e N_p \sigma d}{Ac\tau} \tag{4}$$

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 shorter 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 backscattered photon energy. A pulsed CO_2 laser with high peak power was chosen to produce the backscattered photons with maximum energy 3.03MeV and to match the repetition rate of electron beam in transport line of SRRC. The schematic drawing of the whole system was shown in fig. 2.



fig. 2 The designed experimental setup

A. Optical System

The laser beam was designed to pass a beam expander, a mirror, a focus lens, and a mirror with a hole. The hole was there to clear the path of the backscattered

0-7803-1203-1/93\$03.00©1993 IEEE

photons to the detector. We chose a suitable expanded beam size to decrease the laser beam loss due to the hole on the second mirror. An expander with suitable expanding rate was chosen to increase the backscattered photon number. After a series of calculation, the functional dependents of the laser beam size at different location w(z) on the focal length and the location of the focus lens is shown below.

$$w = \sqrt{\frac{A^2 + (Az + B)^2 \frac{\lambda^2}{\pi^2 w_0^4}}{[A \times (Cz + D) - (Az + B) \times C] \frac{1}{w_0^2}}}$$
(5)

where w is the laser beam size, A,B,C,D are the values of the entries of the transformation matrix (also called as ABCD matrix) of the system which we are considering. λ is the laser wavelength, w_o is the original laser beam waist, and z is the longitudinal position with origin at the location of the focus lens. The dependent of the focal length and the location of the focus lens are through the ABCD and the z. The comparison of the laser beam size change for different focal lengths was shown in fig.3.



ing, o moet beam one vor regitaumar rotation 2

For the beam profile change of the Gaussian beam and the effect of the hole on the mirror, we correct eq. (4) to

$$Y = \frac{2P\sigma N_e}{k_1 c} \int_{z_1}^{z_2} (\overline{A} - \frac{A_h}{A_e}) \frac{dz}{\pi w^2}$$
(6)

where P is the power of the laser light, σ is the total cross section of Compton scattering, w is the radius of the laser light. A_h is the transverse beam size of the lost laser beam which was due to the hole on the mirror #2 and A_e is that of the electron beam. \overline{A} is the smaller one of 1 and A₁/A_e, where A₁ is the transverse beam size of the laser beam, and z₁ to z₂ is the interaction region of the laser beam and the electron beam. The 3D plot of the photon yield vs. the expanding rate of the expander and the focal length of the focus lens was shown in fig. 4. The optimum condition was chosen as that the expanding rate is triple and focal length is 6 meter.



fig. 4 Photon yield vs. the expanding rate and the focal length

B. Detection System

The detection techniques of high energy photon of 1 MeV order of magnitude is universally applied. The coaxial HPGe detector was chosen for the reason of good detector resolution, therefore increasing the accuracy of the beam energy measurement. However at the same time, the detection efficiency of the coaxial HPGe is lower than that of other types. The definition of the intrinsic efficiency of HPGe is

$$\epsilon_{int} = \frac{detected_photon_number}{photon_number_into_the_detector}$$
(7)

rewrite as

$$\varepsilon_{\rm int} = \varepsilon \times \frac{A}{A_a} \tag{8}$$

where ε is the absolute efficiency of HPGe, A and A_a are the area of source to detector sphere and the HPGe front surface respectively. The empirical formula of relative efficiency of HPGe was shown as ^[4]

$$\log \varepsilon = const. + S\log E + C(\log E)^2$$

$$S = a\log(V_{ac}) + b$$
(9)

where E is the gamma ray energy, a=0.6246, b=-2.136, V_{ac} is the active volume of HPGe, S is the slope of the efficiency curve, and C(logE)² is the second order corrected term. The empirical formula is useful in the range up to 3.55 MeV. By those theoretical calculations, we plotted the scattered photon energy vs. photon number as shown in fig. 5. Finally we can estimate the detected backscattered photon number by taking the detector efficiency into account.



fig. 5 Theoretical results of scattered photon energy vs. photon number.

C.. Error Analysis

In our study, we take 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 predict the backscattered photon energy spread Δk_2 by the square root sum :

$$\frac{\Delta k_2}{k_2} = \sqrt{\left(\frac{2\Delta E_e}{E_e}\right)^2 + \left(\frac{\Delta k_1}{k_1}\right)^2 + (Res)^2}$$
(10)

The calculated value of the backscattered photon energy spread at 3.03 MeV is 0.5%.

The energy uncertainty of the 1.3 GeV electron beam is to be 0.25%.

IV. DISCUSSION

During these studies, we simplified the condition of the 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)The effect of the electron beam divergence was not taken into account because the scattered photon energy of the non-head-on collision is smaller than that of the headon collision. Therefore, the electron beam divergence will cause the decrease of the maximum energy photon number. The result is that the sharpness of the maximum energy spectrum will become dull.

V. REFERENCE

[1] R. Rossmanith and R. Schmidt, Laser Diagnostics in High Energy Accelerators, **DESY** M-81/24 (1981)

[2] T. Yamazaki, et al., Generation of Quasimonochromatiz Photon Beams from Compton Backscattered Laser Light at ETL Electron Storage Ring. *IEEE Trans. Nucl. Sci.* **32** (1985) 3406-3408

[3] F. R. Arutyuanin and V. A. Tumanian, The Compton Effect on Relativistic Electrons and the Possibility of Obtanding High Energy Beams, *Phys. Lett.* **1** April (1963) 176-178

[4] Cao Zhong, Empirical Relation between Efficiency and Volume of HPGe Detectors, *Nucl. Instr. and Meth.* A262(1987) 439-440

*Supported by the National Science Council of ROC, Contract NSC 81-0417-E-007-545 and SRRC, ROC.

Department of Physics, National Tsing-Hua University, Hsinchu, Taiwan 30043, ROC