ACCURATE ENERGY MEASUREMENT OF AN ELECTRON BEAM IN A STORAGE RING USING COMPTON SCATTERING TECHNIQUE *

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Abstract

A gamma-ray beam produced by Compton scattering of a laser beam and a relativistic electron beam has been used to determine electron beam parameters. In order to accurately measure the electron beam energy, a fitting model based upon Compton scattering cross section is introduced in this paper. With this model, we have successfully determined the energy of the electron beam in Duke storage ring with a relative uncertainty of 3×10^{-5} using a Compton gamma beam from the High Intensity γ-ray Source (HIγS) facility at Duke University.

INTRODUCTION

A gamma-ray beam produced by Compton scattering of a laser beam and an electron beam carries the information of the electron beam. The high energy edge of the gamma-ray beam spectrum can be used to determine electron beam parameters, such as the beam centroid energy and energy spread. In several published works [1, 2, 3], the high energy edge of the gamma beam spectrum was simply expressed as a convolution between a modified step function and a Gaussian function. The influences of the gamma beam collimation as well as the electron beam emittance on the gamma beam spectrum were not taken into account. However, under many circumstances these influences could have a significant impact on the accuracy of electron beam energy measurements.

To overcome this problem, we have developed a new fitting model which can describe the gamma beam spectrum in detail while taking into account the collimation and emittance effects. Using this model, we have accurately measured the energy of the electron beam in the Duke storage ring with a relative uncertainty of 3×10^{-5}.

SPECTRUM DESCRIPTION

Based upon the Compton scattering cross section, the angular and energy distribution of the gamma photons produced by the collision of electron and laser bunches can be expressed as [4]

$$\frac{d^2N_\gamma}{d\Omega_L dE_\gamma} = N_e N_p \int \frac{d^2\sigma}{d\Omega dE_\gamma} c(1-\beta\cos\theta_i) \times f_e(\mathbf{V},\mathbf{p}_e,t) f_p(\mathbf{V},\mathbf{k},t) d\mathbf{p}_e d\mathbf{k} d\mathbf{V} dt, \quad (1)$$

where dN_γ is the number of the gamma photons in an energy range of E_γ to $E_\gamma + dE_\gamma$ and solid angle $d\Omega_L$ viewed in a laboratory frame; N_e and N_p are the total numbers of electrons and laser photons in their bunches; $d\sigma/d\Omega$ is the angular differential cross section for Compton scattering; c is the speed of light; $\beta = v/c$ is the velocity of the electron scaled by the speed of the light; θ_i is the angle between the momenta of the incident electron and photon. $f_e(\mathbf{V},\mathbf{p}_e,t)$ and $f_p(\mathbf{V},\mathbf{k},t)$ are the phase space distribution functions of the electron and photon beams. The integration is computed for the entire collision time and volume as well as the momenta of electrons and laser photons via $\int \cdots d\mathbf{p}_e d\mathbf{k} d\mathbf{V} dt$.

Assuming Gaussian distributions of the electron and laser beams, neglecting the vertical emittance of the electron beam and the energy spread of the laser beam, and further assuming head-on collisions happening at the waist of the laser beam, the energy spectrum of the collimated gamma beam can be obtained by partially integrating Eq. (1) [4],

$$\frac{dN_\gamma}{dE_\gamma} = \frac{r_e^2 L^2 N_e N_p}{2\pi^2 \hbar c \beta_0 \sqrt{\zeta_x} \sigma_\gamma \sigma_{\theta x}} \int_{-y_o}^{y_o} \int_{-x_o}^{x_o} \int_{-\theta_{xmax}}^{\theta_{xmax}} \left(\frac{\bar{\gamma}}{1+2\bar{\gamma}a}\right) \times \left\{ \frac{1}{4}\left[\frac{4\bar{\gamma}^2 E_p}{E_\gamma(1+\bar{\gamma}^2\theta_f^2)} + \frac{E_\gamma(1+\bar{\gamma}^2\theta_f^2)}{4\bar{\gamma}^2 E_p}\right] - \frac{\bar{\gamma}^2\theta_f^2}{(1+\bar{\gamma}^2\theta_f^2)^2} \right\} \times \exp\left(-\frac{(\theta_x - x_c)^2}{2\sigma_{\theta_x}^2} - \frac{(\bar{\gamma}-\gamma_0)^2}{2\sigma_\gamma^2}\right) d\theta_x dx_c dy_c, \quad (2)$$

where

$$\bar{\gamma} = \frac{2E_\gamma a}{4E_p - E_\gamma\theta_f^2}\left(1+\sqrt{1+\frac{4E_p - E_\gamma\theta_f^2}{4a^2 E_\gamma}}\right);$$

$$a = \frac{E_p}{mc^2};\ \theta_f^2 = \theta_x^2 + (\frac{y_c}{L})^2;\ \sigma_{\theta x} = \sqrt{\frac{\varepsilon_x \xi_x}{\beta_x \zeta_x}};$$

$$\xi_x = 1 + (\frac{\beta_x}{L})^2 + \frac{2k\beta_x\varepsilon_x}{\beta_0};\ \zeta_x = 1 + \frac{2k\beta_x\varepsilon_x}{\beta_0};$$

$$\theta_{xmax} = \sqrt{\frac{4E_p}{E_\gamma} - (\frac{y_c}{L})^2};$$

r_e is the classical electron radius; $\hbar$ is the reduced Planck constant; ε_x and β_x are the emittance and the beta function of the electron beam in the horizontal direction, respectively; $\gamma_0 = E_e/mc^2$ and $\sigma_\gamma = \sigma_{E_e}/mc^2$ represent

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the electron beam energy and energy spread normalized by mc^2, respectively; E_p is the laser photon energy; β_0 and $k = E_p/(\hbar c)$ are the Rayleigh range and wavenumber of the laser beam, respectively; L is the distance between the collision point and the collimator; x_o and y_o are half widths of horizontal and vertical apertures, and for a circular aperture, the radius of the aperture is given by $R = \sqrt{x_o^2 + y_o^2}$. Based upon the assumption of far field collimation ($L \gg R$), the solid angle $d\Omega_L$ in Eq. (1) has been replaced by $dx_c dy_c/L^2$, where x_c and y_c are integration variables ranging from $-x_o$ to x_o and from $-y_o$ to y_o, respectively.

The collimator misalignment effect can been easily introduced in Eq. (2) by replacing the integration variables x_c and y_c with $x_c + x_e$ and $y_c + y_e$, respectively, where x_e and y_e are the misalignment offsets of the collimator in the horizontal and vertical directions with respect to the gamma beam center.

In order to use Eq. (2) to describe the energy spectrum dN_γ/dE_γ of a collimated Compton gamma-ray beam, the integrations with respect to $dx_c, dy_c, d\theta_x$ in Eq. (2) must be evaluated numerically. For this purpose, a numerical integration code has been developed [4]. The spectra calculated using this code for the different misalignment conditions of the collimator are shown in Fig. 1. Clearly, when the misalignment of the collimator is small compared to the radius of the collimation aperture, the misalignment mainly affects the low energy edge of the spectrum, while leaving the the high energy edge unchanged.

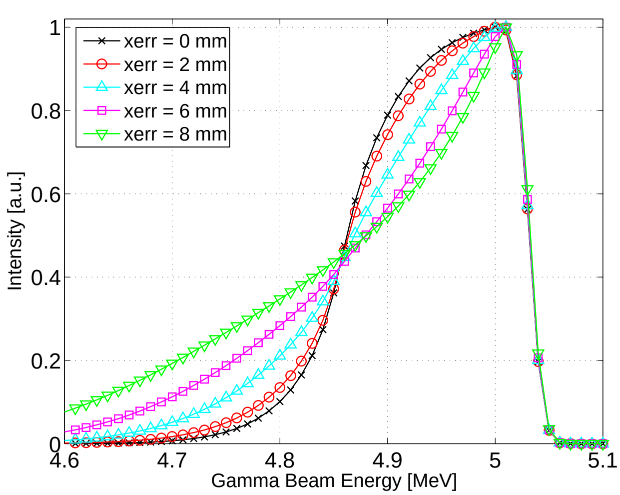

Figure 1: The energy spectrum of gamma-ray beam produced by Compton scattering of a 460 MeV electtron beam with a 790 nm laser beam. The gamma beam is collimated by a collimator with radius of 12.7 mm placed 60 m downstream of the collision point. The spectrum is calculated for different alignment of the collimator from 0.0 mm to 8.0 mm in the horizontal direction.

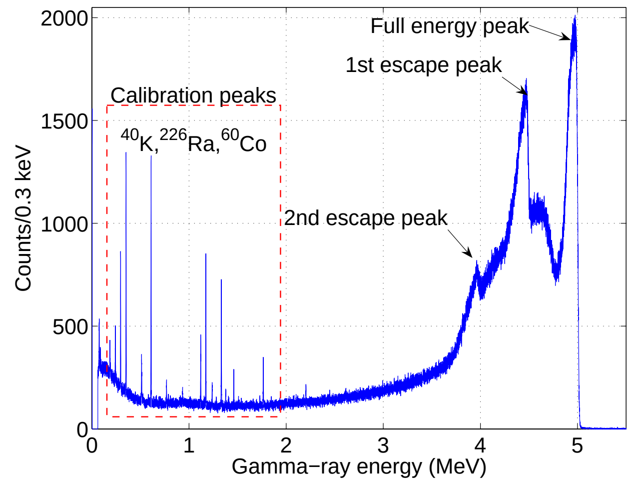

Figure 3: A typical HIγS beam spectrum measured by a large volume 123% efficiency HPGe detector. The radiation sources of ^{226}Ra and ^{60}Co as well as the nature background from ^{40}K are used in the real time for the detector energy calibration.

MEASUREMENT

The schematic of the High Intensity γ-ray Source (HIγS) facility [6] at Duke university is shown in Fig. 2. The gamma-ray beam at HIγS is generated by colliding a Free-Electron Laser (FEL) [7] beam inside the laser resonator with an electron beam in the storage ring. The electron beam is first generated and accelerated to 180 MeV in a linear accelerator. The electron beam energy is then ramped up to a desired value in a booster synchrotron before injecting into the storage ring. The electron beam, consisting of two bunches separated by a half of the storage ring circumference, is used to drive the FEL. The FEL photons from the first (second) electron bunch collide with electrons in the second (first) bunch. The resultant high intensity gamma beam is transported in vacuum to the gamma beam target room. A lead collimator is placed 60 meters downstream of the collision point and before the target room.

The energy spectrum of the gamma beam is measured using a large volume 123% HPGe detector installed at the end of the target room 10 meters downstream from the collimator. The gamma-ray radiation sources of ^{226}Ra and ^{60}Co as well as the nature background from ^{40}K are used for the detector energy calibration. The electron beam emittance and FEL wavelength are recorded by a synchrotron radiation beam profile monitor and a spectrometer, respectively.

A HIγS beam collimated by a lead aperture with radius of 12.7 mm is used to determine the electron beam energy and energy spread. A typical measured gamma beam spectrum with the simultaneously recorded gamma-ray calibration peaks are shown in Fig. 3.

Using Eq. (2), the nonliner least square fitting method

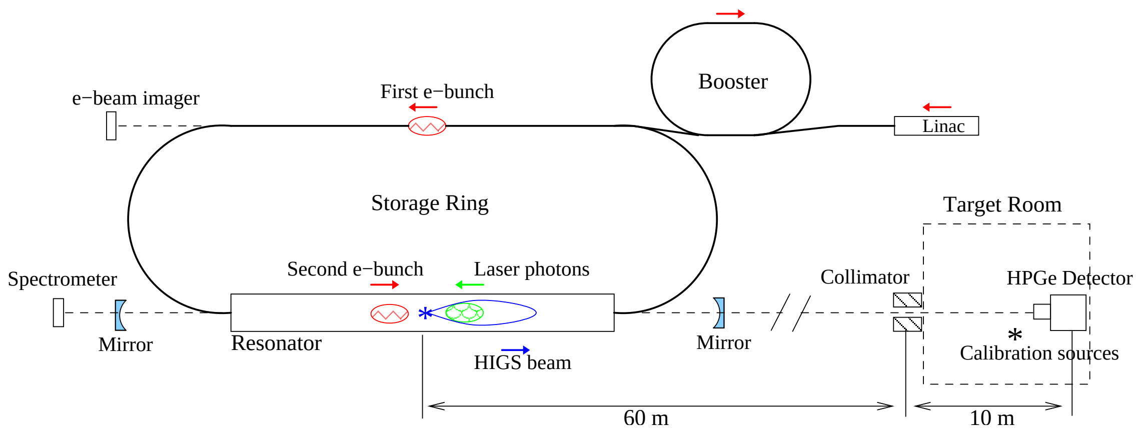

Figure 2: Schematic of the HIγS beam production and measurement at Duke University.

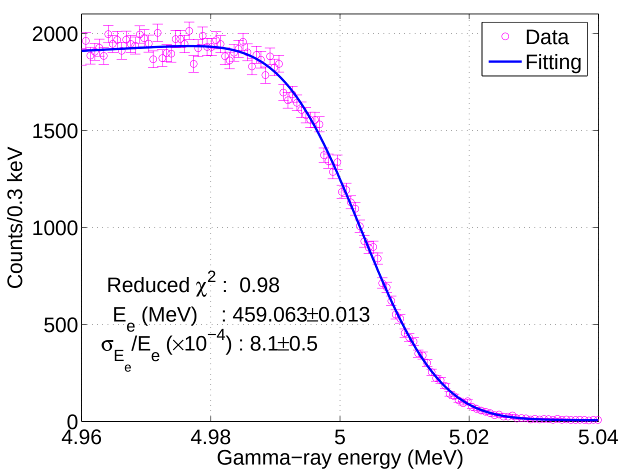

Figure 4: Illustration of the fitting on the high energy edge of the measured gamma beam spectrum. The goodness-of-fit is given by the reduced χ^2. The determined electron beam energy E_e and relative energy spread σ_{E_e}/E_e as well as the overall uncertainties associated with them are also shown.

is applied to the high energy edge of the measured gamma beam spectrum using electron beam energy γ_0 (E_e/mc^2) and energy spread σ_γ (σ_{E_e}/mc^2) as parameters. To speed up the fitting process, a parallel computing technique which involves 32 central processing units (CPUs) of the Duke Shared Cluster Resource (DSCR) [5] is applied. The fitting result is illustrated in Fig. 4. The fit electron beam energy is 459.063 MeV.

The accuracy of the electron beam energy measurement is mainly affected by the uncertainties in the determination of the gamma beam spectrum edge as well as the FEL peak wavelength. These uncertainties can be further divided into two types: systematic errors and statistical errors. The systematic errors arise from the calibration of the HPGe detector and the spectrometer, while the statistical errors arise from the count fluctuations in the measured gamma beam spectrum and the measured FEL spectrum. The overall uncertainty δE_e (68% confidence level) of the electron beam energy measurement is given by the square root of the quadratic sum of the individul uncertainty contribution δE_e^i, i.e., $\delta E_e = \sqrt{\Sigma_i(\delta E_e^i)^2}$. In this measurement, the overall uncertainty of the energy measurement is estimated about 0.013 MeV. Thus, the relative uncertainty of 3×10^{-5}, including both systematic and statistical errors, is achieved for the electron beam energy measurement.

SUMMARY

Based upon the Compton scattering cross section, we have derived a formula to describe the energy spectrum of a collimated Compton gamma-ray beam. Using this formula as a fitting model and a gamma-ray beam from the High Intensity γ-ray source (HIγS) facility, we have successfully measured the electron beam energy with a relative uncertainty of 3×10^{-5} for 460 MeV beam in Duke Storage ring.

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