END-TO-END SPECTRUM RECONSTRUCTION OF COMPTON GAMMA-RAY BEAM TO DETERMINE ELECTRON BEAM PARAMETERS*

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Abstract

A gamma-ray beam produced by Compton scattering of a laser beam with a relativistic electron beam has been used to determine the electron beam parameters. In the past, the electron beam energy and energy spread were directly fit from the high energy edge of a measured gamma beam spectrum using a gamma-ray detector. However, due to non-ideal response of the detector, the measured spectrum cannot represent the true energy distribution of the gamma-ray beam. Thus, the electron beam energy and energy spread could not be accurately determined from the measured gamma beam spectrum. In this paper, we will present a novel end-to-end spectrum reconstruction method to accurately extract the energy distribution of the gamma-ray beam from the measured gamma beam spectrum. Using this method we have accurately determined the energy and energy spread of the electron beam in Duke storage ring using a Compton gamma-ray beam from the High Intensity γ-ray Source (HIγS) facility.

INTRODUCTION

A gamma-ray beam produced by Compton scattering of an electron beam and a laser beam carries the information of the electron beam. Such a gamma-ray beam can be used to determine the electron beam parameters. Typically, the energy and energy spread of electron beam can be directly fit [1–5] from the high energy edge of the gamma beam spectrum measured using a high purity germanium detector (HPGe). However, due to non-ideal response of the detector, the measured spectrum usually has a structure of a full energy peak, two escape peaks, a Compton edge and a Compton plateau. Especially when the span of the high energy edge of the gamma beam spectrum is comparable to or wider than the energy separation between the full energy peak and the first escape peak, the full energy peak cannot be easily identified shown in Fig. 1. As a result, the accurate values of the electron beam parameters cannot be directly determined from the measured gamma beam spectrum.

Using a spectrum unfolding technique, the gamma beam energy distribution can be extracted from the measured spectrum. However, in the past the detector response function used in the spectrum unfolding was simulated by a simple Monte Carlo code in which an isotropic gamma-ray event generator is used. For a Compton scattered gamma-ray beam, however, this simulation method could lead to an inaccurate detector response function, because it neglects the detailed spatial and energy distributions of the gamma-ray beam [6].

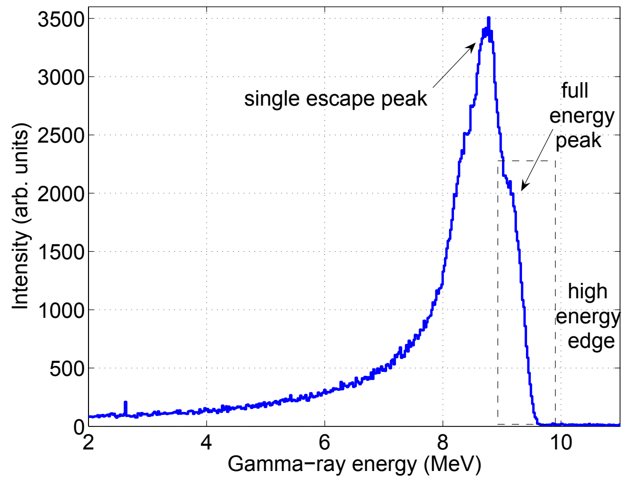

Figure 1: Measured energy spectrum of a gamma-ray beam produced by Compton scattering of a 466 MeV electron beam with a 789 nm Free-electron Laser beam at the High Intensity γ-ray Source (HIγS) facility. The gamma-ray beam is collimated by a lead aperture with a radius of 12.7 mm placed 60 m downstream from the collision point. After collimation, the gamma-ray beam is detected by a large volume 123% HPGe detector placed downstream 10 m from the collimator.

In this paper, we will present a novel end-to-end gamma-ray spectrum reconstruction method which completely models the process of the Compton gamma-ray beam production, collimation, transportation and detection. This method not only allows to accurately unfold the gamma beam spectrum, but also allows to determine the electron beam energy and energy spread with a high degree of accuracy. This work is of critical important to the frontier application research using the High Intensity Gamma-ray Source (HIγS) [7] powered by an intra-cavity Free-Electron Laser (FEL) [8] at Duke University.

SPECTRUM RECONSTRUCTION

The end-to-end spectrum reconstruction method is based upon completely modeling of the Compton gamma beam

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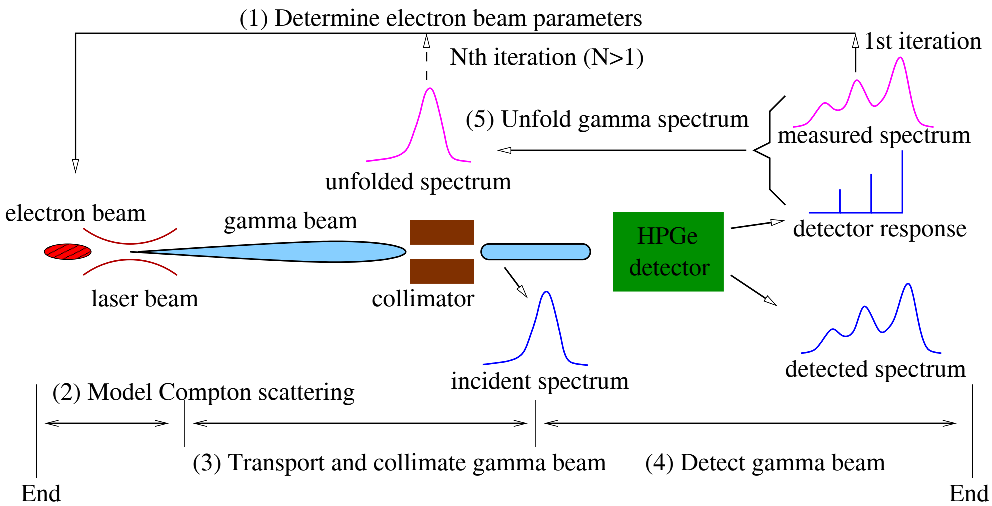

Figure 2: Illustration of the end-to-end spectrum reconstruction method to recover the energy distribution of a Compton gamma-ray beam. A few iterations are typically adequate to find a convergent energy distribution as well as the electron beam energy and energy spread.

production, collimation, transportation, and detection. A Monte Carlo Compton scattering code (MCCMPT) developed at Duke [9] is used to model the Compton scattering process, while the well-known Geant4 toolkit [10] is used to model the process of gamma beam collimation, transport and detection. To facilitate the simulations, the MCCMPT code is integrated into Geant4 code and a new code G4CMPT is formed.

In order to model the Compton scattering process, the incoming beam parameters, such as the laser beam wavelength, the electron beam energy, energy spread and emittance, must be accurately known. The laser wavelength and electron beam emittance can be directly measured by a spectrometer and a synchrotron radiation monitor, respectively. Although the accurate values of the electron beam energy and energy spread are undetermined, their trial values fit from the measured gamma beam spectrum can be used to model the Compton scattering process at the beginning of the spectrum reconstruction.

The procedures to reconstruct the gamma beam distribution and to determine electron beam energy and energy spread are illustrated in Fig. 2, and explained as follows:

1. To make an estimate of the electron beam energy and energy spread by fitting the high energy edge of the measured gamma-ray beam spectrum;

2. To simulate the Compton scattering of an electron beam and a laser beam and produce a Compton gamma-ray beam;

3. To transport and collimate the Compton gamma-ray beam. After collimation, the spectrum of the gamma-ray beam prior to the detection (namely, the incident spectrum) is obtained;

4. To transport the collimated gamma-ray beam to the detector and simulate the interaction of the beam with the detector. After the detection, a detector response matrix and a detected spectrum are obtained;

5. To use the *Gold algorithm iteration* [2, 11] method to unfold the measured gamma-ray beam spectrum.

6. Stop if a convergence is found between the simulated incident spectrum and the unfolded spectrum; otherwise, go to step 1, but the high energy edge of the unfolded spectrum are used to determine the electron beam energy and energy spread.

Typically, a few iterations are adequate to find a convergent energy and energy spread of the electron beam as well as a convergent gamma beam energy distribution.

APPLICATION

We have successfully applied the end-to-end spectrum reconstruction method to unfold the measured gamma beam spectrum shown in Fig. 1. In this same process the end-to-end method also allows us to determine the electron beam energy and energy spread with a high degree of accuracy.

Since the full energy peak and escape peaks of the measured gamma beam spectrum are completely folded together, the determined electron beam parameters in the first iteration are not accurate. As a result, the simulated incident spectrum and unfolded spectrum are not convergent to each other as shown in Fig. 3(a). In the second iteration, instead of the measured spectrum, the unfolded spectrum obtained in the first iteration is used to determine the electron beam energy and energy spread; the resultant simulated incident spectrum and unfolded spectrum has a good agreement as shown in Fig. 3(b). In this iteration a good agreement is also found between the measured spectrum

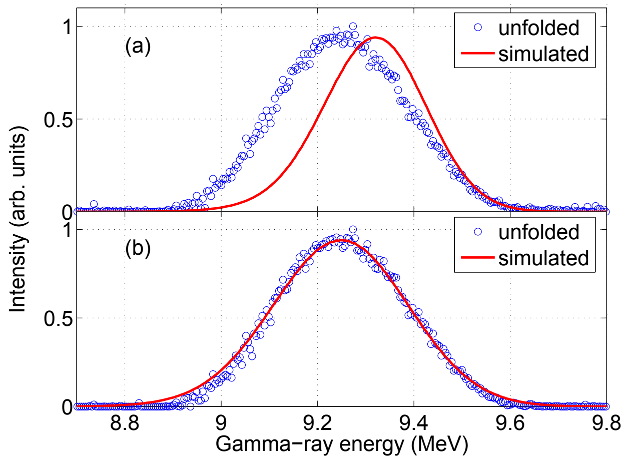

Figure 3: The unfolded energy spectrum compared with the simulated incident spectrum for a 9 MeV HIγS beam. Two iteration is needed in order to find a convergence between the unfolded spectrum and simulated spectrum. (a) First iteration; (b) second iteration.

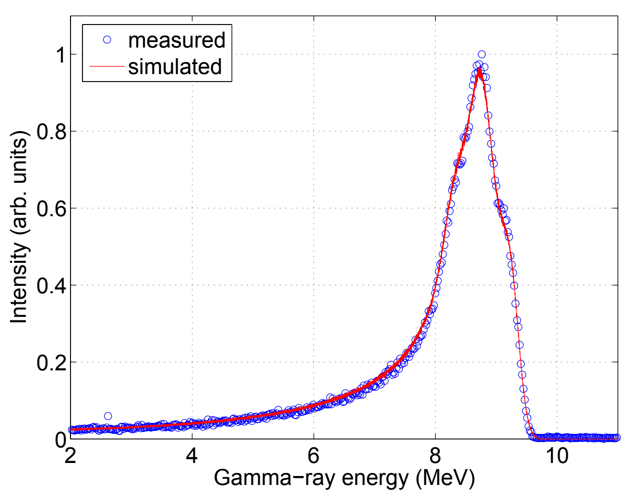

Figure 4: The simulated energy spectrum compared with the measured spectrum shown in Fig. 1.

and simulated spectrum as shown in Fig. 4. Thus, the unfolded spectrum after second iteration can be used for the accurate determination of the electron beam parameters. The fitting model introduced in [2] has been used to fit the high energy edge of the spectrum, and the fitting result is shown in Fig. 5.

Thus, with the assistant of this end-to-end spectrum reconstruction method, the electron beam energy and energy spread are accurately determined with value 521.47 ± 13 MeV and $(7.2 \pm 0.7) \times 10^{-3}$, respectively. The detailed discussion about the measurement uncertainties are given in [2].

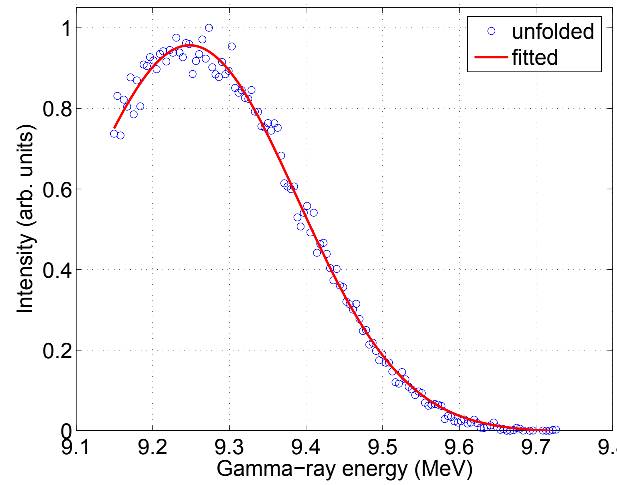

Figure 5: Illustration of the fitting on the high energy edge of the unfolded gamma beam spectrum. The non-linear least squares fitting method is applied to fit the model introduced in [2].

SUMMARY

In this paper, we presented a novel end-to-end spectrum reconstruction method to recover the energy distribution of a gamma beam from its measured spectrum. With the assistant of this method, we accurately determined the energy and energy spread of the electron beam in the Duke storage ring using a Compton gamma-ray beam from the High Intensity γ-ray Source facility at Duke University.

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