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New Technique for Absolute Beam Energy Calibration in e^+e^- Accelerators.

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Abstract

A new approach for absolute beam energy measurement with a use of the kinematic properties of the Compton backscattering is suggested. Under reasonable gamma-ray beam detector requirements, it possesses absolute accuracy for beam energy measurement up to the value of 10^{-4}.

1 INTRODUCTION

There are several approaches to measure the electron beam energy by use of Compton backscattering kinematic properties. The Compton backscattering kinematics is shown on Fig.1: a photon with energy ω_0 and wave vector $\vec{k_0}$ is incident on a high energy electron ($\varepsilon = |\vec{p}|$) with angle α. In the final state an energetic γ-quantum $(\omega, \vec{k})$ is scattered by angle θ.

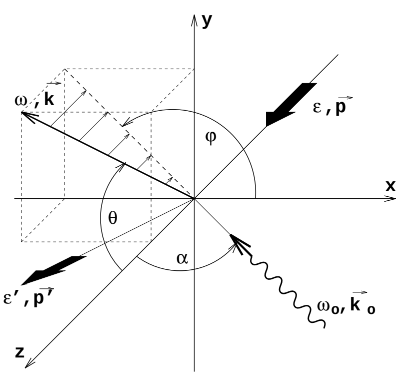

Figure 1: Compton backscattering kinematics

Main kinematic parameters of the Compton backscattering are coupled by the following formula [1]:

$$\omega = \varepsilon \frac{\lambda}{1 + \lambda + (\theta\varepsilon/m_e c^2)^2}; \quad \lambda = \frac{4\varepsilon\omega_o}{(m_e c^2)^2} cos^2\frac{\alpha}{2} \quad (1)$$

Since that, one can measure the Compton energy spectrum for a couple or more laser wavelengths and then determine the electron beam energy ε from the relative positions of the energy spectrum edges ($\theta = 0$). Although these edges are very sharp and thus may be measured with a very high accuracy, one must exactly know the linearity of the energy scale of the detector used for the measurements to obtain the high accuracy for the electron beam energy calibration.

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2 IDEA

The main idea of the current suggestion is an attempt to skip through the problem of having a perfect detector for direct Compton energy spectra measurements. As far as the laser-electron interaction is the interaction of two monochromatic beams, there is an unambiguous correlation between the scattered photon energy ω and its emission angle θ, described by equation (1). Thus one can measure the photon emission angle instead of its energy. If we use two laser lines to scatter on the electron beam: $\omega_1 = \omega_0$ and $\omega_2 = K \cdot \omega_0$ ($K > 1$), then for any monochromatic line ω in the backscattered photon energy spectra (below the backscattered photons energy spectrum edge for ω_1) we have the following equation:

$$\frac{\lambda}{1 + \lambda + (\theta_1\varepsilon/m_e c^2)^2} = \frac{K\lambda}{1 + K\lambda + (\theta_2\varepsilon/m_e c^2)^2}, \quad (2)$$

where θ_1 and θ_2 are the photon scattering angles for laser lines with the energies ω_1, ω_2. This gives a possibilty to determine the electron beam energy by measuring the θ_1 and θ_2 angles:

$$\varepsilon = m_e c^2 \sqrt{\frac{K - 1}{\theta_2^2 - K\theta_1^2}}, \quad (3)$$

To perform the calibration of the electron beam energy ε we suggest to obtain the Compton backscattering for two laser lines on the electron beam, and then to measure the backscattered photon energy and coordinates by the γ-quanta detector, situated at distance D from the interaction area along the photon beam propagation direction. The essential difference from the mentioned above idea of direct measurement of the Compton energy spectra edges is that the sense of the energy spectrometer in our case is only to select the same energy range for the backscattering photons from both initial laser photons energies.

First, let's assume that we have the γ-quanta detector with perfect energy and space resolution, and that the electron beam itself has zero transverse size and all electrons momenta are collinear. In this ideal case any monochromatic line ω in the energy spectra for ω_1 and ω_2 laser photons energies gives delta-function distributions over radius $R = D\tan(\theta)$ in the coordinate detector plane. The accuracy for the beam energy calibration is then given by the expression:

$$\frac{\delta\varepsilon}{\varepsilon} \simeq \frac{1}{D}\sqrt{(\frac{\varepsilon}{m_e c^2})^2 \Delta R^2 + \Delta D^2}; \qquad (4)$$

Where ΔR and ΔD are the accuracies for the radius R and detector distance D. From this expression we can mention that for the beam energy $\varepsilon = 5.0\ GeV$ and detector distance $D = 50\ m$ we need to measure the radius R with accuracy about $1\ \mu m$ to have the $\simeq 10^{-4}$ accuracy for ε. The values of m_e, c and K are considered to be known with the accuracy of 10^{-8} and are treated as constants in the further discussion.

In real life this narrow R-distribution is smeared by the following parameters:

- the width of the choozen energy range in the backscattered photon energy spectrum;
- energy resolution of the spectrometer;
- space resolution of the coordinate detector;
- energy, coordinate and angular spreads in the electron beam.

3 RADIUS MEASUREMENT

We have to determine the radius that corresponds to the selected energy diapason in the backscattered photon spectra for both the ω_1 and ω_2 laser lines from the coordinate distributions of these photons on the coordinate detector. This section describes one of the possible approaches to solve the problem. We assume that the coordinate distribution of the backscattered photons is described by the following formula:

$$f(x, y) = \frac{1}{4\pi^2 \sigma_x \sigma_y R_0} \cdot$$
$$\cdot \int_0^{2\pi} \exp\left[-\frac{(R_0 \cos\varphi - x)^2}{2\sigma_x^2} - \frac{(R_0 \sin\varphi - y)^2}{2\sigma_y^2}\right] d\varphi; \qquad (5)$$

that is the convolution of the ring with radius R_0 with the two-dimensional Gaussian for coordinates x and y.

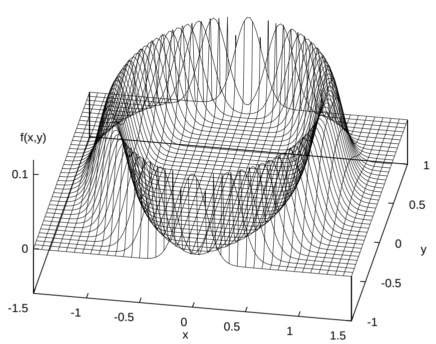

Figure 2: The $f(x, y)$ function

The ring with radius R_0 corresponds the angle θ for the backscattering photons of energy ω, and all the factors from the list in the end of the previous section give the Gaussian dispersions σ_x and σ_y. By simple integration of the $f(x, y)$ function over x or y coordinates, we have the functions to fit the y and x coordinate distributions of the backscattered photons on the coordinate detector, and then determine the R_0. The plot for the $f(x, y)$ function is given on Figure 2.

4 NUMERICAL EXAMPLE

The Monte Carlo simulations were performed to obtain the possible experimental accuracy of the electron beam energy measurement. The following parameters were set for the Compton backscattering process simulation:

- electron beam energy ε = 5 GeV (that is the case of VEPP-4M collider [2]);
- photon energies ω_1 = 1.165 eV and ω_2 = 2.33 eV that corresponds to the first and the second harmonics of Nd:YAG laser (this means $K = 2$);
- electron-laser beams interaction angle $\alpha = \pi/2$, that allows to obtain accurate knowledge of the electron-photon interaction area position;
- Gaussian dispersions for the electron beam transverse sizes σ_y = 100 μm, σ_x = 200 μm;

The backscattered photon energy spectra for two laser photon energies ω_1 = 1.165 eV and ω_2 = 2.33 eV are plotted on Figure 3. The dashed region (100 MeV width) was divided into 1 MeV intervals, for each of them the x and y coordinate distributions were simulated on the coordinate detector.

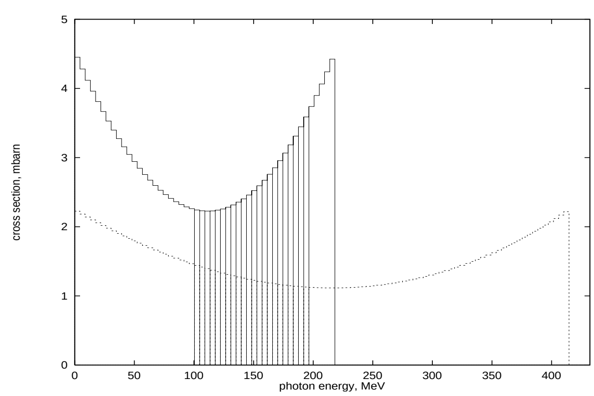

Figure 3: The backscattered photons energy spectra

Next set of simulation parameters describes the detector for the backscattered photons:

- The coordinate detector Gaussian dispersions for the space resolution σ_y = 100 μm, σ_x = 100 μm;
- The coordinate detector distance from the electron-photon interaction area and its accuracy $D \pm \Delta D$ = 7500 $\pm$ 0.5 cm.

Coordinates and energy are measured in channels: one coordinate channel equals 100 μm, one energy channel equals 0.1 MeV. The coordinate distribution of backscattered photons for one of the energy intervals is shown on Figure 4:

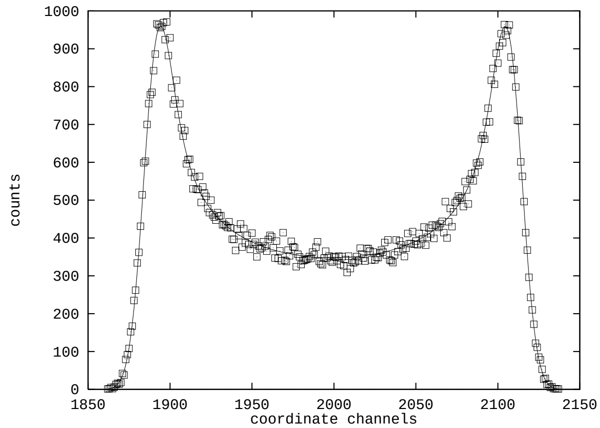

Figure 4: X-coordinate distribution of backscattered photons for ω_0 = 2.33 eV, ε = 5 GeV. Energy interval fixed by the specrometer is $139 - 140$ MeV. Empty squares - result of Monte Carlo simulation, the fit was done as it was described in section 3. χ^2=1.047

The dependence of the relative statistical error in radius measurement from the number of counts in histogram is given on Figure 5:

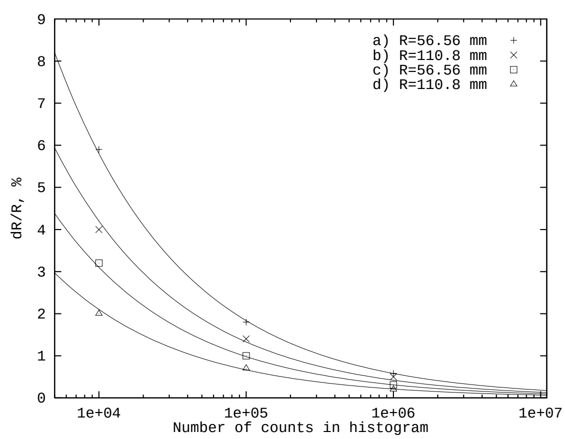

Figure 5: Dependence of the relative statistical error in radius measurement from the number of counts in histogram. The labels in the corner are in the same order (from top to bottom) as the lines and points on the plot. The Gaussian angular spread in the electron beam equals $0.2 \cdot 10^{-4}$ rad for cases a), c) and $0.1 \cdot 10^{-4}$ rad for cases b), d)

Figure 5 shows that the errors in radius measurement obey to the $1/\sqrt{N}$ law. Then we have to deal with a systematical error in ε measurement, originating from the width of each energy interval, selected by the spectrometer. The point is that we actually have two different energy spectra shapes for the two selected laser photon energies ω_1 and ω_2, as it was shown on Figure 3. The non-zero width of the selected interval gives the difference between the average energy (inside each interval) for these two spectra. The effective width of the interval is determined by the convolution of the selected range with the resolution of the spectrometer. Therefore there is no sense to select the intervals narrower then the spectrometer energy resolution. The dependence of the systematical beam energy shift on the spectrometer energy resolution is given on Figure 6:

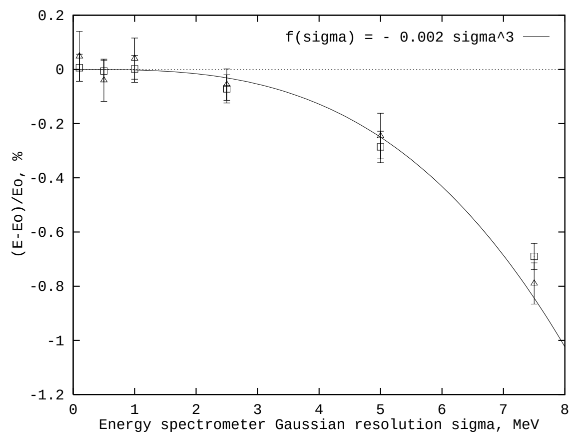

Figure 6: The dependence of the $(\varepsilon - \varepsilon_0)/\varepsilon_0$ on the σ_ω.

The absolute value of the electron beam energy on Figure 6 was determined by averaging the values, obtained from 20 energy intervals of 1 MeV width. The systematical shift must be taken into account for correct electron beam energy measurement.

5 DISCUSSION

A new approach to measure an absolute electron beam energy by the coordinate-sensitive detector has been suggested in this report. The statistical errors for radiuses determination could be minimized to the level of 10^{-3} or even better by increasing the experimental statistics to the value of 10^7 or more photons per histogram. A numerical estimations for the method accuracy at the electron beam energy ε=5 GeV shows that the main source of systematical errors is in the difference of the energy spectra shapes for two laser lines in the selected energy range. These systematical shift in the absolute beam energy calibration have to be significantly smaller for higher beam energies, cause the arbitrary energy resolution of the photon spectrometer will be much better for this case.

6 REFERENCES

[1] V.B.Berestetsky, E.M.Lifshitz, L.P.Pitaevsky. Relativistic Quantum Theory, Moscow, 1968

[2] G.Ya. Kezerashvili et al. Nucl. Inst. Meth. B 145 (1998) 40-48