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ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ
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Compton Edge Electron Beam Energy Spectrometer

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Abstract

A technique based on the Compton scattering of visible light is proposed for measuring the absolute energies of electrons in a stored electron beam as well as in a linear collider. The absolute energy of the beam is determined by the measurement of the absolute energy spectrum of scattered electrons near Compton edge.

The Monte Carlo simulations taking into account the real parameters of GRAAL, CEBAF and SLC facilities show that the evaluation of Compton edge and hence the energy of the electron beam can be performed with a precision below or about 10^{-4} level in second.

It is shown that an absolute and accurate determination of the electron beam energy can be performed by the measurement of the ratios of Compton edges from two different laser lines, i.e. without determination of the absolute values of Compton edges.

1 Te(iniques for Measuring Energy

The en gy of stored electron beam can be measured accuratly by de-polarization (see e.g. [1]).

The standard way of the determination of a linac beam energy is to measure the deflection angle of the beam in a magnetic field. In order to obtain the absolute energy both $\int Bdl$ and the deflection angle have to be measured [2].

Several modifications of this technique exist, e.g. by using synchrotron light [3].

The resonant de-polarization method as well as the determination of the deflection angle of the beam in a magnetic field allow one to determine the ratio E/m_e, where E and m_e are the total and rest energies of the electron respectively.

By using the Compton effect the Lorentz factor of the beam $\gamma = 1/\sqrt{1-\beta^2}$, where β is the electron relative velocity, can be measured [4-6]. This is not only a new and simple method for measuring energy, but also allow to check some basic prin(ples of special relativity [7].

In this method the Lorentz factor can be determined by the measurement of the absolute energy of backscattered photons [4,5, 8,9], or by the measurement of the absolute or relative energies of scattered electrons [10].

In our previous papers [5,8,10] we consider the cases where by the help of collimation of backward scattered photons it was possible to have monochromatic photons or recoil electrons. But this is true for parallel beams, when $(d\vartheta_2\gamma)^2 \leq 10^{-2}$, where $d\vartheta_2$ is the incident electron beam angular divergence. In this paper we propose to evaluate the absolute beam energy by the measurement of the inclusive energy spectrum of scattered electrons near the kinematical (Compton) edge. It is shown by the help of Monte Carlo calculation that the precisions of the order of 10^{-4} can be reached on the existing or planing setups of GRAAL, CEBAF and SLC.

2 The Basic Formulas of Compton Scattering on Moving Electrons

Below, formulas for Compton scattering on moving electrons [11,12] are given for the case of our interest [13].

In the interaction region a photon with energy ω_{01} is scattered on an electron with energy E_1 at a small collision angle α (Fig.1). The energy of the scattered photon ω_{21} depends on its angle ϑ_γ relative to the motion of the incident electron as follows:

$$\omega_{21} = \frac{\omega_{01}}{1 + (\vartheta_\gamma/\vartheta_0)^2} \quad (1)$$

where

$$\omega_{21}^{max} = \frac{x}{x+1} E_1 \quad (2)$$

$$\vartheta_0 = \frac{m_e}{E_1}\sqrt{x+1} \quad (3)$$

$$x = \frac{4E_1\omega_{01}cos^2(\alpha/2)}{m_e^2c^4} \quad (4)$$

where ω_{21}^{max} is the maximum photon energy. For example: $E_1 = 6.0\ GeV$, $\omega_{01} = 3.54\ eV$ (Argon ion laser) x=0.325 and $\omega_{21}^{max}/E_1 = 0.254$;

The photon and electron scattering angles are unique functions of the photon energy:

$$\vartheta_\gamma(y_\gamma) = \vartheta_0\sqrt{\frac{y_\gamma^{max}}{y_\gamma} - 1} \quad (5)$$

$$\vartheta_e(y_\gamma) = \vartheta_\gamma\frac{y_\gamma}{1-y_\gamma} \quad (6)$$

where $y_\gamma = \omega_{21}/E_1$. These functions for $x = 0.325$ are displayed in Fig.2.

The energy spectrum of the scattered photons is defined by the cross section

$$\frac{1}{\sigma_c}\frac{d\sigma_c}{dy_\gamma} \equiv f(x, y_\gamma) = \frac{2\sigma_0}{x\sigma_c}\left(\frac{1}{1-y_\gamma} + 1 - y_\gamma - 4r(1-r)\right) \quad (7)$$

where

$$y_\gamma \leq y_\gamma^{max} = \frac{x}{x+1}$$

$$r = \frac{y_\gamma}{x(1-y_\gamma)} \leq 1$$

$$\sigma_0 = \pi\left(\frac{e^2}{m_ec^2}\right)^2 = 2.5 \times 10^{-25}\ cm^2.$$

The total Compton cross section for the nonpolarization case is

$$\sigma_c = \frac{2\sigma_0}{x}\left((1 - \frac{4}{x} - \frac{8}{x^2})ln(x+1) + \frac{1}{2} + \frac{8}{x} - \frac{1}{2(x+1)^2}\right) \quad (8)$$

The absolute value of the energy of incident electrons can be determined by the measurement of the absolute value of the Compton edges of scattered electrons or photons as well as by means of the determination of the ratios: 1. $y_e^{min} = E_{21}^{min}/E_1$; 2. $y_\gamma^{max} = \omega_{21}^{max}/E_1$; 3. $a_e = E_{21}^{min}/E_{22}^{min}$; 4. $a_\gamma = \omega_{22}^{max}/\omega_{21}^{max}$, where E_{21}^{min}, E_{22}^{min} ($\omega_{21}^{max}, \omega_{22}^{max}$) are the values of Compton edges of scattered electrons (photons) from two different laser lines (ω_{01}, ω_{02}) and $y_e = 1 - y_\gamma$; $y_e^{min} = 1 - y_\gamma^{max} = 1/(1+x)$.

For example in the case of 2 and 3 we have

$$x = \frac{y_\gamma^{max}}{1 - y_\gamma^{max}} \quad (9)$$

and

$$x = \frac{1 - a_e}{a_e(1 - \omega_{02}/\omega_{01})} \quad (10)$$

3 Result of Monte Carlo Simulations of the Compton Edge Spectrometer

The main idea of this method based on the inclusive energy spectrum measurement near the kinematical (Compton) edge of electrons scattered on the laser photons. In this paragraph we present the results of Monte Carlo simulations of such spectrometer. This calculations were carried out by the help of formula (7) taking into account the energy spread of scattered electrons. We consider the absolute energy determination of the electron beams of GRAAL[14], CEBAF[15] and SLC[16] electron accelerators.

The total bound-widths of the Compton edge of the GRAAL and CEBAF facilities ($E_1 = 6000\ MeV$) are 15 MeV and 3 MeV (FWHM), respectively. These values include all the effects due to the electron beam phase space and energy resolution of the recoil electron spectrometer (tagged system). For the total band width of the Compton edge of the electron SLC beam we use the value 150 MeV, which include the effect of the energy dispersion of incident electron beam only ($FWHM/E_1 = 3 \times 10^{-3}$). The expected energy distribution of scattered electrons near Compton edges obtained by Monte Carlo simulation for GRAAL, CEBAF and SLC are presented in Fig.5,6,7. The corresponding laser frequencies for GRAAL, CEBAF and SLC are 3.54, 3.54 and 1.17 eV, respectively. The total number of events is 2×10^5.

Fitting the Monte Carlo spectrum presented in Fig.5-7 by the convolution of the resolution function with the theoretical cross section, using a fitting algorithm based on Gaussian statistics, 6000 ± 0.09 MeV, 6000 ± 0.06 MeV and 49999 ± 2.9 MeV with an effective χ^2 per degree of freedom of 0.90, 0.98 and 1.28 can be extracted respectively. The obtained results are presented in Table 1.

Table.1 The used parameters and extracted values of the CEBAF, GRAAL and SLC beam energies and the dispersions obtained with the help of formula 7.

device	E_1 MeV	FWHM MeV	ω_{01} eV	E_1^{Fit} MeV	χ^2/NDF
CEBAF	6000.	3.0	1.17	6000.0 ± 0.025	1.04
	6000.	3.0	3.54	6000.0 ± 0.060	0.98
GRAAL	6000.	15.0	1.17	6000.0 ± 0.500	1.35
	6000.	15.0	3.54	6000.0 ± 0.090	0.90
SLC	50000.	150.0	1.17	49999.0 ± 2.9	1.28
	50000.	150.0	2.34	49997.0 ± 7.0	1.2

The results obtained by the help of formula (10) using the ratio $a_e = y_{e,1}^{min}/y_{e,2}^{min}$ from two different laser lines $(\omega_{01}, \omega_{02})$ are presented in Table 2. In this case, the absolute calibration of recoil electron spectrometer is not necessary. The only requirement is linearity of the recoil electron spectrometer.

Table.2 The same as in Table 1, obtained with the help of formula 10. The extracted values of the a_e and their dispersions are given in addition.

Device	E_1 MeV	FWHM MeV	ω_{01} eV	ω_{02} eV	a_e	E_1^{Fit} MeV
CEBAF	6000.	3.0	3.54	1.17	0.83564 ± 0.00001	6000.2 ± 0.4
GRAAL	6000.	15.0	3.54	1.17	0.83563 ± 0.00003	6000.5 ± 1.3
SLC	50000.	150.0	3.54	1.17	0.51083 ± 0.00004	$50026. \pm 14.$

4 Practical Issues Concerning a Compton Edge Spectrometer

We consider the case of measuring of the energy distribution of recoil electrons near the Compton edge. Basically the method involves measuring the deflection of recoil electrons in a magnetic field. Therefore, this method requires measurement of the magnetic field integrals and the bending angles. In order to determine the beam momentum to 10^{-4}, both of these quantities must be determined at a level somewhat better than 10^{-4}. For SLC magnets, the attainable accuracy for the absolute value of the field integrals is of the order of 10^{-4} [2].

Since the Compton electron scattering angles are smaller ($\leq 10^{-5} rad, see Fig.2$) than the angular divergence of the beam ($10^{-4} - 10^{-5}$), the scattered and unscattered

electrons remain unsepareted until they pass through dipole magnets. Both beams are dispersed and recoil electrons detected (see Fig. 8).

To determine the bending angles of recoil electrons, multichannel monitors (gaseous or silicon microstrip detectors), mounted on a precision optical table would be used. If center of the magnetic field is known and the distance between the center of magnetic field and monitors is c, the distance between the centroids of the forward scattered photons (and hence the centroid of the incident electron beam) and recoil electron is a, then the bend angle is $\vartheta = a/c$. Assuming the errors in these quantities are independent:

$$\frac{d\vartheta}{\vartheta} = \sqrt{(\frac{da}{a})^2 + (\frac{dc}{c})^2} \tag{11}$$

Usually, c is of the orders of 10 m, a about 1 m, therefor to reach the precession better than 10^{-4} we will have $da = dc \leq 100\mu m$.

Let us consider more detail the case, when the coordinates of the center of magnetic field is not known. In this case to determine the bending angles of recoil electrons two rows of monitors, mounted on a precision optical table, would be used. If the distance between the front and rear monitors is c_1 and the distances between the centroids of the forward scattered photon beam and recoil electrons on the front and rear monitors are a_1 and b_1, respectively, then the bend angle is $\vartheta = (a_1 - b_1)/c_1$, and

$$\frac{d\vartheta}{\vartheta} = \sqrt{\frac{(da_1)^2 + (db_1)^2}{(a_1 - b_1)^2} + (\frac{dc_1}{c_1})^2} \tag{12}$$

For $a_1 = 0.8m$, $b_1 = 1.2m$, $c_1 = 2.0m(\vartheta = 8.6^o)$ and $da_1 = db_1 = dc_1 = 15\mu$ this gives

$$\frac{d\vartheta}{\vartheta} = 7.1 \times 10^{-5}$$

Therefor the centroids of the forward scattered photon beam and the positions of the recoil electrons on the two rows of monitors must be determined to the level of 15μ.

The above requirement implies high resolution position monitors for recoil electrons as well as accurate measurement of the relative position of each monitor on the optical table. Regarding the centroid measurement of the forward scattered photons, the required photon detector must have good position resolution but need not measure the photon energy. One may use a detector consisting of a series of tungsten converter foils each followed by a pair of $x - y$ silicon μ-strip. With such a detector a detection efficiency is about 50% and a position resolution is about 12μ is feasible [17].

For the recoil electron beam, the μ-strip silicon or gaseous detectors seems promising. The resolution quoted for this devices is about 10μ. One of the main problems is that the backscattered photons has a fairly large angular spread. One must determine the centroid width much greater accuracy than this width.

The width of the angular distribution of backscattered photons in radians, is about $1/\gamma$, when the energy of photons not determined. With a beam energy of 5.0 GeV the width is 100 μrad. It is conceivable that the centroid angle can be measured to within roughly 1/10 of the width. Since our requirement is $7.5\mu rad$, this is not problematic if the transverse dimensions of the incident beam of the order or lesser than 100μ and 30μ in the case of first (when center of magnetic field is known) and second (when center of magnetic field is not known) cases, respectively.

The angular and energy divergence of the incident beam influence on the energy resolution of the each individual events. As follows from the Monte Carlo simulations, the absolute value of mean energy of the beam can be determined within and order of magnitude better than the energy spread of the recoil electrons.

The expected intensities of back scattered laser photons at GRAAL[14], CEBAF[17] and SLC[16] is $10^7 photon \times sec^{-1}$ or higher. Therefore the absolute energy of the incident beam can be determined by this method with the precision of about 10^{-4} in second.

5 Summary

The results of the simulations shown above indicate that it is possible to make an absolute beam energy measurement to an accuracy of about 10^{-4} of the GRAAL, CEBAF and SLC electron beams. The method has several advantages.

First, since this technique involves measurement of the recoil electrons scattered on the laser photons, it is simple and non-destructive to the electron beam.

Second, this method can be employed for the stored beams as well as extracted ones. Therefore, this method can be used for checking existing technique, which have been suggested as candidates for a 10^{-4} absolute energy determination of electron beams, comparing difference methods with the resonance de-polarization method.

Third, by having all the detectors mounted common precision table their relative positions can be accurately measured and controlled, another advantage which allowed to carry out absolute calibration of magnetic spectrometers.

Finnaly, this method is not much sensitive to the angular spread of the incident beam.

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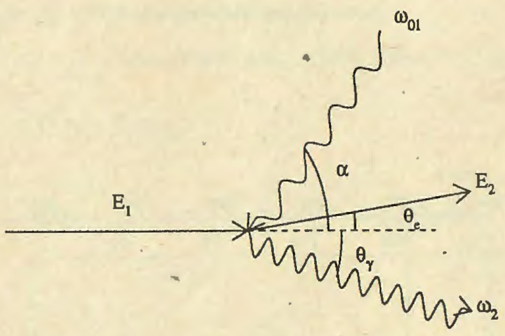

Figure 1: Kinematics of Compton scattering.

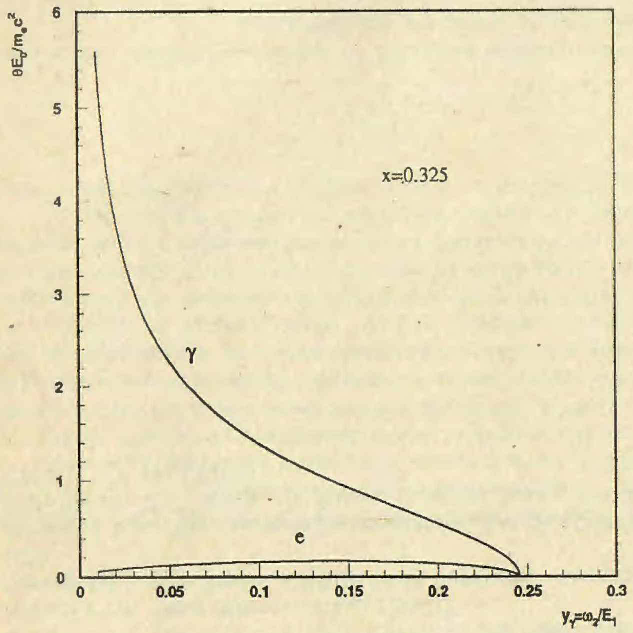

Figure 2: Electron and photon scattering angles vs photon energy for x=0.325.

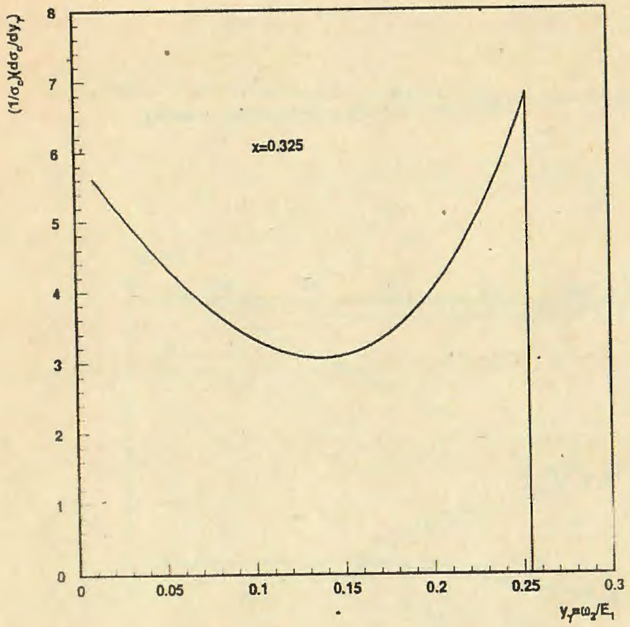

Figure 3: Energy spectra of scattered photons.

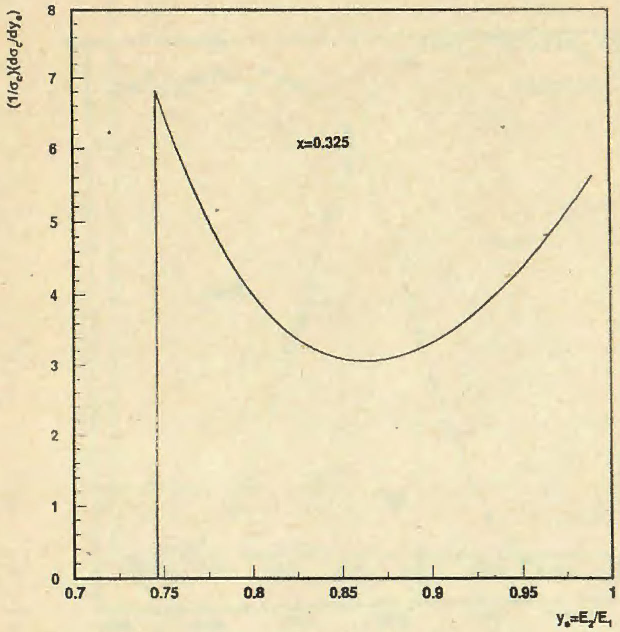

Figure 4: Energy spectra of scattered electrons.

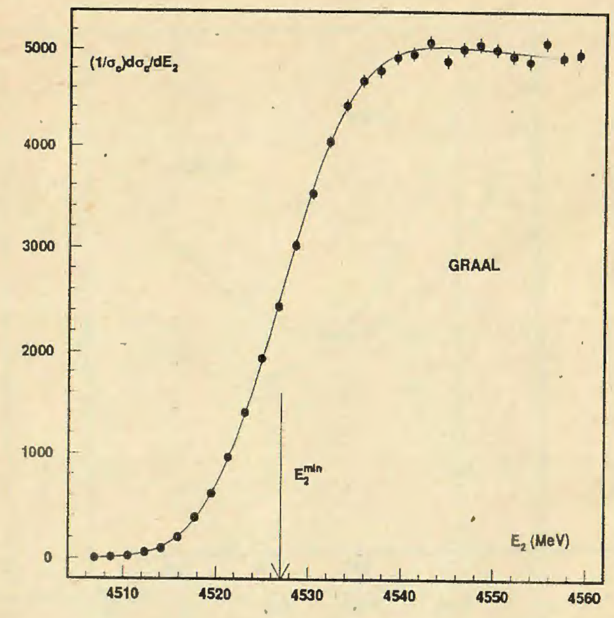

Figure 5: Energy spectrum of scattered e^- near Compton edge. The do[illegible]ow the MC simulation result, the curve is a result of the fit. The extracted electron beam ener[illegible] 6000 ± 0.09 MeV with a true beam energy 6000 MeV and laser photon ener[illegible]4 eV.

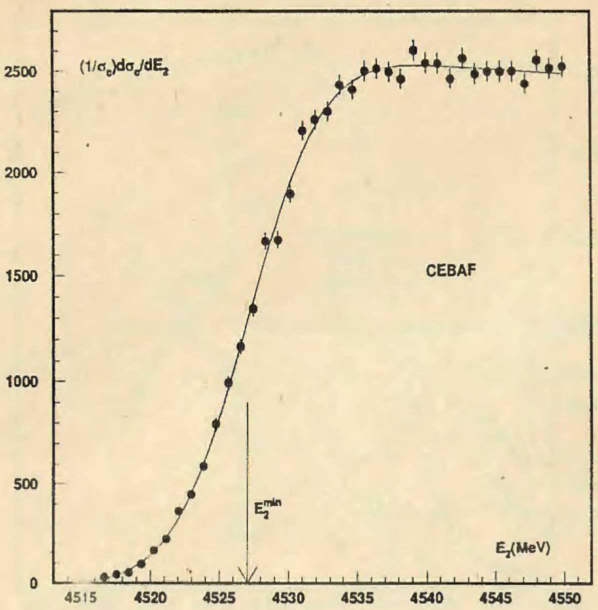

Figure 6: The same [illegible] in Fig.5 for the CEBAF electron beam. The extracted electron beam energy is 6000 ± 0.06 M[illegible] with a true beam energy 6000 MeV and laser photon energy 3.54 eV.

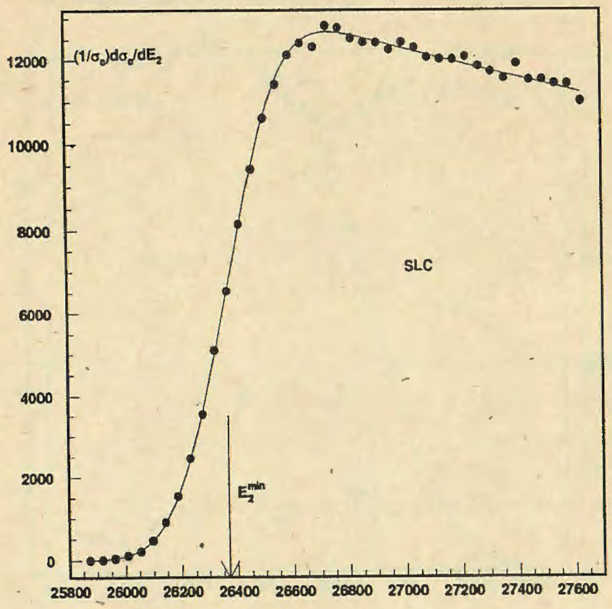

Figure 7: The same as in Fig.5 for the SLC electron beam. The extracted electron beam energy is 49999 ± 2.9 MeV with a true beam energy 50000 MeV and laser photon energy 1.17 eV.

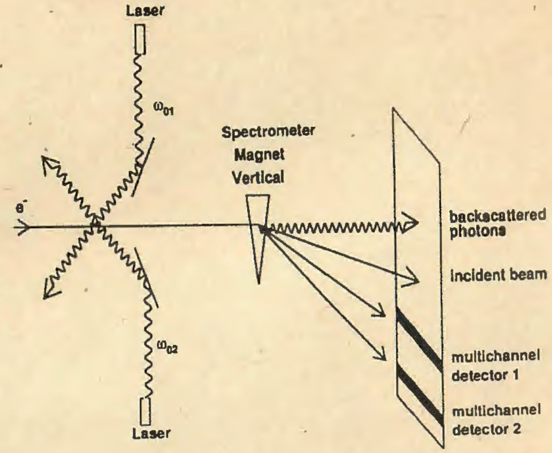

Figure 8: Conceptual design of the experimental setup.

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