ABSOLUTE ENERGY MEASUREMENT IN e^{-} e^{+} COLLIDERS*

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Abstract

A technique based on the Compton scattering of linearly polarized visible light is proposed for measuring the absolute energy of an electron beam in a linear collider. In the vicinity of 90 degrees in the rest frame of the electron the ratio of the cross-section for different linear light polarizations depends strongly on the absolute energy of the beam. This is especially true when the backscattering rates with light polarized perpendicular to the scattering plane is compared with light polarized in the scattering plane. As a result, the absolute energy of the beam can be determined to a high degree of precision by measuring the ratio of two counting rates. Using a strong laser field (e.g. that in a Fabry-Perot resonant cavity), the measurement can be performed in a fraction of a second. Examples of possible practical arrangements are given.

I. TECHNIQUES FOR MEASURING ENERGY

The energy of a stored electron beam can be measured both elegantly and accuratly by depolarization.

In linacs, however, a similarly elegant method does not exist.

Up to now the energy of a linac beam could be measured in several ways.

a.) The standard way is to measure the deflection angle of the beam in a magnetic field. In order to obtain the absolute energy both $\int B.dl$ and the deflection angle have to be measured.

b.) Several modifications of this technique exist, e.g. by using synchrotron light. A single line of the spectrum is selected and the intensities at various angles are compared [1].

The ratio of the intensity at these two angles varies when the energy changes. The technique can be modified by using two magnets of different strengths. In order to measure the absolute energy the field strength at the emission point has to be measured [2]. This has a clear advantage over a.) since the magnitude $\int B.dl$ no longer has to be known. Only the absolute field strength at the emission point has to be measured using an absolute measuring device such as an NMR.

In a.) and b.) magnets are involved which deflect the beam. By using the Compton effect the energy of the beam can be measured without deflecting the beam. In most of the proposals the energy of the backscattered photons is measured. By measuring the energy of the backscattered photons with the highest energy, γ can be calculated. Unfortunately, it is very difficult to measure the energy of high energy photons with high accuracy. Therefore two concepts were developed.

c.) A laser with low energy photons is used as the source. If the electrons have relatively low energy (less than 5 GeV), the backscattered photons are in the keV range where detectors can measure the energy with high accuracy [3].

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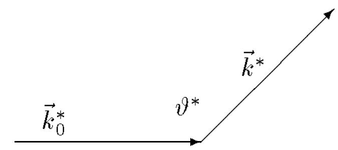

Figure 1. Scattering geometry in the rest frame

d.) Instead of optical photons RF photons are used. The beam traverses a cavity and produces visible photons. The energy of the backscattered visible photons can be analyzed by well known optical techniques [4].

Many variations of this technique exist: for instance, it is possible to use a wiggler instead of a cavity in d.). c.) and d.) only work well when the electron energy is relatively low.

Despite these deficiences, the Compton effect is a very attractive method for performing energy measurements since only two particles (the photon and the electron) are involved in this process.

II. THE BASIC FORMULAS

The Klein-Nishina formula describes the Compton scattering cross-section for arbitrary electron and photon polarization. The formula is usually used in the rest frame of the electron. In the formula, all energy values are normalized to the rest mass of the electron (m_0c^2). The normalized energy k of the incoming photon is E_{phot}/m_0c^2. α is the crossing angle between the electron and the laser beam. In the rest frame of the electron the incoming photon has the energy

$$k_0^* = \gamma k(1 + cos\alpha) \tag{1}$$

Magnitudes with an "*" refer to the rest frame. In the rest frame the laboratory angle α becomes α^*.

$$sin\alpha^* = \frac{1}{\gamma}\frac{sin\alpha}{1 + cos\alpha} \tag{2}$$

After scattering, the energy of the scattered photon changes to

$$k^* = \left(1 - cos\vartheta^* + \frac{1}{k_0^*}\right)^{-1} \tag{3}$$

The definitions of the magnitudes can be found in Fig. 1.

The polarization of the photon is described in the Klein-Nishina formula by a 3-dimensional vector (Stokes parameters): (ξ_1, ξ_2, ξ_3). For an electromagnetic wave

$$E_x = E_0 a_x exp(i(kx - \omega t + \Delta_x))$$
$$E_y = E_0 a_y exp(i(ky - \omega t + \Delta_x)) \tag{4}$$

with

$$a_x^2 + a_y^2 = 1$$

the Stokes parameters are

$$\xi_1 = a_x^2 - a_y^2$$
$$\xi_2 = 2a_x a_y cos(\Delta_x - \Delta_y)$$
$$\xi_3 = 2a_x a_y sin(\Delta_x - \Delta_y) \tag{5}$$

For linearly polarized light in the direction of the x or y axis $\vec{\xi} = (\pm 1, 0, 0)$, for linearly polarized light under 45^0 $\vec{\xi} = (0,1,0)$ and for unpolarized light $\vec{\xi} = (0,0,0)$.

The spin of the electron $\vec{\zeta}$ in the Klein-Nishina formula is a 3-dimensional vector with spin components oriented along the axes x, y and z.

In the rest frame of the electron the differential cross-section for Compton scattering is

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{k^*}{k_0^*}\right)^2 (\Phi_0 + \Phi_1 + \Phi_2) \tag{6}$$

r_0 is the classical electron radius.

$$\Phi_0 = (1 + cos^2\vartheta^*) + (k_0^* - k^*)(1 - cos\vartheta^*)$$
$$\Phi_1 = \xi_1 sin^2\vartheta^*$$
$$\Phi_2 = -\xi_3(1 - cos\vartheta^*)\vec{\zeta}(\vec{k}_0^* cos\vartheta^* + \vec{k}^*) \tag{7}$$

Φ_1 depends on linear polarization. In the following only linearly polarized or unpolarized light is taken into account: Φ_2 is zero.

In the rest frame $d\Omega$ is

$$d\Omega = sin\vartheta^* d\vartheta^* d\varphi \tag{8}$$

φ is the azimuthal angle and frame independent.

The rest frame magnitudes can be transformed into the lab frame in the following way

$$k_x = k_x^*$$
$$k_y = \gamma(k_y^* - k^*)$$
$$k_z = k_z^* \tag{9}$$

And finally the scattering angle in the lab system is

$$sin\vartheta = \frac{1}{\gamma}\frac{sin\vartheta^*}{1 - cos\vartheta^*} \tag{10}$$

In the following the basic idea of the measurement is introduced. For a scattering angle of 90 degrees ($cos\vartheta^* = 0, sin\vartheta^* = 1$) and linearly polarized light

$$\Phi_0 = 1 + (k_0^* - k^*)$$
$$\Phi_1 = \pm 1 \tag{11}$$

The cross-sections for the two different light polarizations are:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\perp,90^0} \approx 2 + \frac{k_0^{*2}}{1 + k_0^*}$$
$$\left(\frac{d\sigma}{d\Omega}\right)_{\|,90^0} \approx \frac{k_0^{*2}}{1 + k_0^*} \tag{12}$$

For unpolarized light and light with a polarization vector of 45 degrees relative to the x and y axis

$$\left(\frac{d\sigma}{d\Omega}\right)_{unpol,90^0} \approx 1 + \frac{k_0^{*2}}{1 + k_0^*} \tag{13}$$

The ratio

$$\left(\frac{d\sigma}{d\Omega}\right)_{\perp,90^0} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{\|,90^0} = \frac{2 + 2k_0^* + k_0^{*2}}{k_0^{*2}} \tag{14}$$

depends only on the energy of the electrons and the energy of the photons: $k_0^* = 2\gamma k$ for α = 0.

In a similar way cross-section ratios at 90^0 can be obtained which have a less complicated dependence on k_0^*:

$$\left[\left(\frac{d\sigma}{d\Omega}\right)_{\perp,90^0} - \left(\frac{d\sigma}{d\Omega}\right)_{unpol,90^0}\right] \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{\|,90^0} =$$
$$\frac{1}{k_0^{*2}} = \frac{1}{4\gamma^2 k^2} \tag{15}$$

These formulas show the principle of the idea. By measuring ratios of counting rates with the Compton effect, the energy can be determined. Since most modern accelerators have Compton polarimeters the measurement can be performed using existing equipment. Energy measurement and polarization measurement with the Compton effect are very similar.

III. PRACTICAL DESIGN

From a practical point of view the flux measurement of photons emitted under 90 degrees is rather difficult. The detector of a polarimeter is usually a shower counter with a limited energy resolution. Thus, only photons within a certain energy range can be measured.

Fig. 2 shows the ratio defined in equation (14) for the energies 40 and 40.4 GeV and a photon energy of 2.5 eV in the vicinity of the 90 degree rest frame angle. Within any given energy interval the cross-section ratio and therefore the counting rate ratio differ significantly within any given energy interval both on the right hand side and left hand side of the minimum. If single photons can be detected and their energy evaluated the absolute energy of the beam can be easily determined when the energy resolution of the shower counter is well known.

The speed of the measurement is determined by the statistical error from the photon flux. The speed of the measurement is clearly a nonlinear function of the energy deviation: strong deviations produce a higher counting rate difference than do smaller ones. Fig. 2 calculated for a 10% energy deviation, produces a ratio which differs by more than a factor of 2 in the vicinity of 20 GeV.

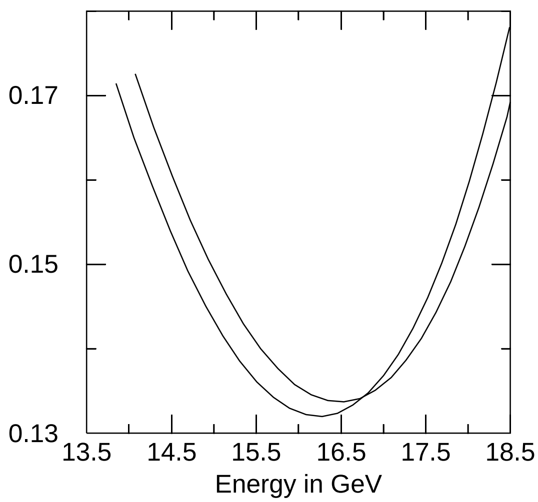

Figure 2. *The ratio equation (14) for 2 electron energies, 40 and 40.4 GeV. The cross section ratio is plotted for photon energies in the vicinity of 90^0 (rest frame of the electron)*

In order to measure the energy with an accuracy of 10^{-3}, 10^6 photons have to be collected by the detector. With a single photon technique the measuring time would be too long.

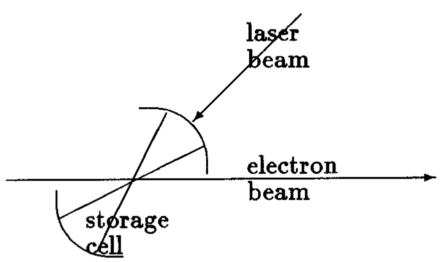

Figure 3. Principle of the storage cell laser-electron beam interaction. The intensity of the incoming laser beam is amplified by the Fabry-Perot cavity.

In order to increase the backscattering rate, the use of so-called storage cells was proposed. The idea was first used in gravity wave detectors. Two mirrors surround the electron beam as shown in Fig. 3. The beam is reflected forwards and backwards between the two mirrors. A typical intensity enhancement factor is 10^4. In laboratory tests enhancement factors of 3×10^4 are obtained. In almost all accelerators the typical backscattering rate in a polarimeter without a storage cell is in the order of 1 kHz. With the storage cell this rate can be increased to 10^7 Hz. With this technique, the energy (as well as the polarization) can be measured with an accuracy of greater than 10^{-3} in less than one second. An accuracy of 10^{-4} can be obtained in approximately 10 sec.

It is obvious that this energy measuring device can be used as a sensor in a feedback loop in order to overcome drifts in the net gradients of the cavities. A storage cell is now under development at the University of Virginia, Charlottesville. First beam tests are expected to take place at the beginning of next year [5].

The practical problems connected with the detector design for the backscattered photons are very similar to the calibration problems connected with polarimeters. According to equation (10) the rest frame scattering angle is converted into an angle of $1/\gamma$ in the lab frame. For a 50 GeV beam this angle is 10μrad, for 500 GeV 1μrad. The laser interaction zone and the detector have to be several 100 meters apart from each other. The effect is also smeared out by the emittance. The influence of the emittance on the effect can be determined in a practical way by measuring the spectrum of the backscattered photons and then comparing it with calculations. Systematic detector and aperture errors can be eliminated by changing the direction of the linear polarization.

IV. ACKNOWLEDGEMENTS

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