FCC-ee BEAM ENERGY MEASUREMENT SUGGESTION*

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Abstract

An approach for beam energy calibration at future circular electron-positron collider (FCC-ee) is suggested. The method is based on a magnetic spectrometer, but does not require absolute knowledge of its bending field. Inverse Compton scattering of laser radiation on the electron beam provides accurate calibration of the bending force. Due to scattering kinematics, the beam energy determination is based on the laser wavelength together with accurate measurement of the ratio of deflection angles. The approach has no serious limitations in the electron beam energy range. The same apparatus allows to measure the electron beam polarization.

INTRODUCTION

Accurate knowledge of the beam energy in experiments on lepton colliders provides direct access to collision energy. This knowledge has always been a tremendous advantage for performing precise measurements of particle masses, shapes of the resonance structures, etc.

The present accuracy of the mass scale in high-energy physics is established mostly due to the resonant depolarization technique, which had been used at various e^+e^- colliders like VEPP-2M, SPEAR, DORIS, CESR, VEPP-4(M), LEP. The resonant depolarization approach provides ultimate precision ($\Delta E_0/E_0 \simeq 10^{-6}$) for instant beam energy determination through measurement of the spin precession frequency. However, preparation of and control over polarized beams is not always possible and usually consumes significant amount of time and decreases the overall luminosity integral. At high beam energies the beam polarimetry is usually based on laser backscattering, a process which is sensitive to both transverse and longitudinal polarization of electrons [1, 2].

In case when an experiment requires precise measurement of the beam energy, it is very important to have several complementary approaches possessing high sensitivity at least to relative beam energy changes. This helps to determine the beam energy behaviour during data acquisition time as well as to perform various cross-checks and eliminate possible errors. In storage rings the beam energy is usually derived from continuous measurements of the bending fields in a number of dipoles. The relationship between the measured fields and the beam energy is defined via magnetic model of the storage ring, which is calibrated against precise measurements of the beam energy, e. g. by resonant depolarisation [3, 4].

At LEP 2 the beam energy "was verified by three independent methods: the flux-loop, which is sensitive to the bending field of all the dipoles of LEP; the spectrometer, which determines the energy through measurements of the deflection of the beam in a magnet of known integrated field; and an analysis of the variation of the synchrotron tune with the total RF voltage".

Compton Backscattering of Laser Radiation

Here let us make a brief introduction to another approach for the absolute beam energy determination. It was implemented for the last ten years at e^+e^- colliders VEPP-4M [3], BEPC-II [5] and VEPP-2000 [6, 7].

When the photon with energy ω_0 is scattered towards the relativistic electron with energy E_0, this electron gives significant part of its energy to the scattered photon, even in case when $\omega_0 \ll E_0$. Maximum energy loss of the electron occurs when the scattered photon propagates exactly along the electron momentum, carrying out ω_{max} energy:

$$\omega_{max} = E_0 \frac{\kappa}{1+\kappa}\,, \tag{1}$$

where $\kappa = 4\omega_0 E_0/m^2$. Electron mass m is a well established parameter, $\Delta m/m \simeq 2 \cdot 10^{-8}$. If one uses a laser as a source of photons for scattering, the order of about 1 ppm relative accuracy for the ω_0 value is practically not a problem. Thus, if one can measure ω_{max} in absolute units, electron energy E_0 could be easily obtained from Eq. 1 with roughly twice better relative precision than ω_{max} measurement.

The particular case when this approach is good enough is when ω_{max} belongs to the energy range between 100 keV and 10 MeV. Here the HPGe[1] detectors possess *high energy resolution* and *sufficient efficiency*. What is also very important is that in this energy range the *absolute scale calibration is possible* due to well-known energies of nuclear γ-sources. By now the backscattering of laser radiation is a well established approach for beam energy measurement with an accuracy $\Delta E_0/E_0 \lesssim 5 \cdot 10^{-5}$, but its application is limited for the beam energies $E_0 \lesssim 2$ GeV.

For further consideration we note that for a relativistic electron one can neglect ω_0 in the energy balance of scattering, i. e. the minimal electron energy after scattering $E_{min} = E_0 - \omega_{max}$, and from Eq. 1 one has:

$$E_{min} = E_0 \frac{1}{1+\kappa}\,. \tag{2}$$

THE SUGGESTION

One of the beam energy measurement approaches at LEP (1997-2000) was the LEP spectrometer [4]. The similar concept was proposed for the ILC upstream beam energy spectrometer [2]. When the electron beam passes through

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[1] HPGe – High Purity Germanium detector

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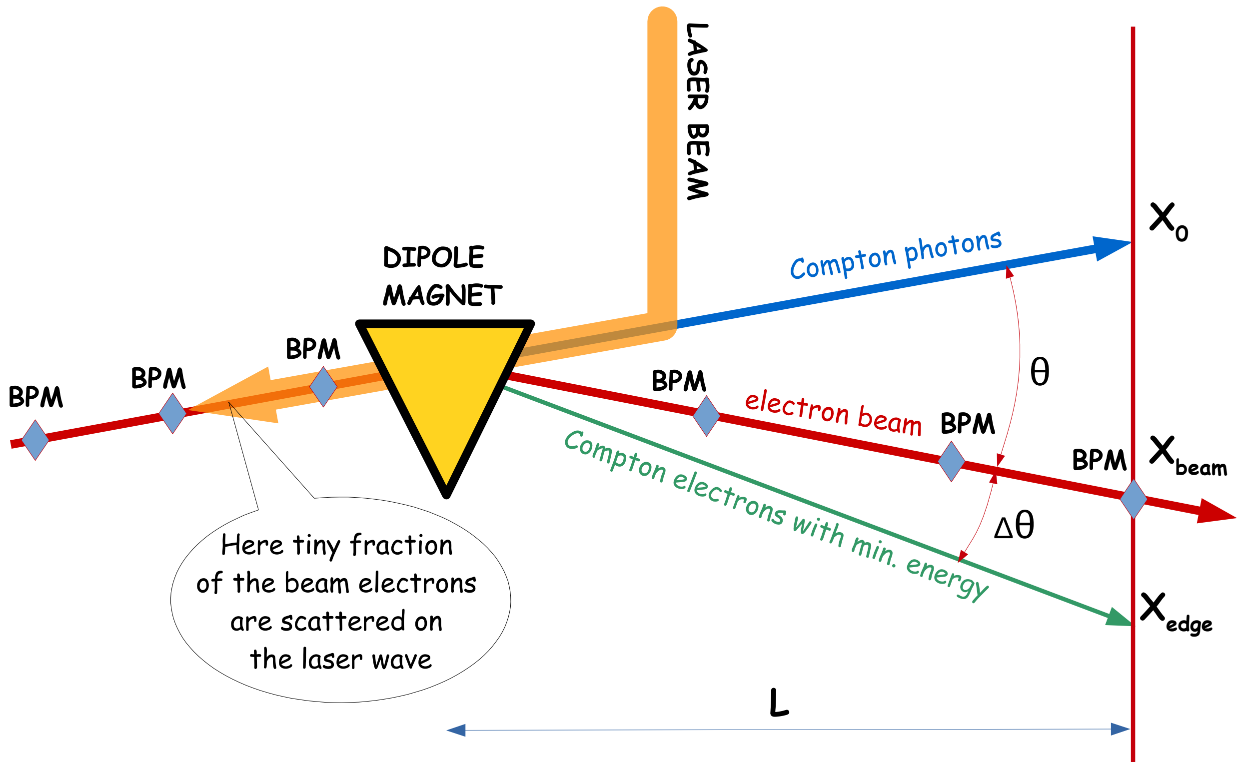

Figure 1: Apparatus layout. If one measures θ and $\Delta\theta$, the beam energy E_0 is determined by equation (5).

the bending magnet, mean electron energy E_0 is derived from the bending field integral and deflection angle θ:

$$\theta = \frac{c \int Bds}{E_0} . \tag{3}$$

Layout of the apparatus for FCC-ee beam energy calibration is shown in Fig. 1. Beam position monitors (BPM) are installed along the beam orbit before and after the bending magnet, allowing to measure the beam deflection angle and thus completely reproduce the conventional spectrometer approach.

In addition (see Fig. 1), laser radiation propagates towards the electron beam, and the electron-photon interaction occurs before electrons enter the dipole magnet. This interaction produces scattered photons and electrons. The number of scattered particles is only a few pieces per bunch, so the affordable low-power laser system may be used, satisfying the requirements of non-destructive instrument.

The electron beam bending angle, θ in Fig. 1, is inverse proportional to the mean beam energy E_0 (see Eq. 3). A deflection angle for the electrons with the energy E_{min} could be obtained by substitution of E_{min} from Eq. 2 instead of E_0 to Eq. 3. Finally, we find that:

$$\frac{\Delta\theta}{\theta} = \kappa = \frac{4\omega_0 E_0}{m^2} . \tag{4}$$

Of course, this simple equality is exact only in the case when the integrals of the magnetic field $\int Bds$ are equal for electrons with either E_0 or E_{min} energies. However, Eq. 4 is not obvious, it was first mentioned as a tool for the beam energy spectrometer calibration in [8].

$\Delta\theta/\theta$ is proportional to ω_0 and E_0, in case when E_0 = 100 GeV and ω_0 = 1 eV one has $\Delta\theta/\theta \simeq 1.53$. With a green laser ($\omega_0$ = 2 eV) this ratio may be doubled, while with IR laser (ω_0 = 0.1 eV) it will be ten times lower.

We suggest to obtain the mean energy of beam electrons from the measurements of deflection angles θ and $\Delta\theta$:

$$E_0 = \frac{\Delta\theta}{\theta} \times \frac{m^2}{4\omega_0} . \tag{5}$$

Vertical line on the right of Fig. 1 is the “detection line”, located at the distance L from the dipole, where one of downstream BPMs is installed: this BPM will measure X_{beam}.

The photon detector measures the space distribution of backscattering photons and determine its mean value X_0. The up-down asymmetry appears in this distribution when the circular polarized laser light is scattered on the electron beam with transverse polarization [1].

The scattered electrons detector provides their distribution along the detection line. This distribution has a sharp edge at X_{edge}, corresponding to the electrons with E_{min} energy. The width (spread) of the edge will be equal to the unscattered beam transverse size at the detection line due to Eq. 4. X_{edge} is going to be obtained from fitting the edge with erfc-like function. The height of the edge depends on lon-

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gitudinal electrons polarization when the circular polarized laser light is scattered on the electron beam [2].

The data of both detectors is collected for many laser shots during some time by the order of several minutes. If $\theta, \Delta\theta \ll 1$ one has

$$\frac{\Delta\theta}{\theta} \simeq \frac{X_{edge} - X_{beam}}{X_{beam} - X_0}, \qquad (6)$$

which allows to use these measurements for beam energy determination by Eq. 5.

Alternatively, the value of θ may be taken from the BPMs data only.

A ough Accuracy stimation

Suppose that we can measure both $[X_{beam} - X_0]$ and $[X_{edge} - X_{beam}]$ with 10 μm accuracy, which seems to be technically possible. In order to achieve the precision of beam energy measurement at the level of $\Delta E/E \simeq 10^{-5}$, one needs to have both $[X_{beam} - X_0]$ and $[X_{edge} - X_{beam}]$ to be about 1 m. This is the case, for example, if the beam bending angle $\theta \simeq 10$ mrad and a free space between the magnet and the "detection line" $L \simeq 100$ m (see Fig. 1). The only way to reduce the bending angle and overall size of the system is to improve the accuracy of coordinate measuremets, it is a challenge that requires more studies.

CONCLUSION

The problem of the beam energy calibration for high energy colliders still does not have a perfect solution. Extensive way of solving the problem is to increase the accuracy of existing methods. In the opinion of the author, no less important is to search for innovative approaches. Let's list the strengths of the present suggestion:

- it aims to measure the absolute energy of the electron beam and does not require precise measurements of magnetic fields in absolute scale;
- backscattering of laser radiation is a proven tool for beam energy calibration at low energy machines;
- conventional spectrometer remains in service and provides *independent information* about the beam energy;
- the calibration procedure for coordinate-sensitive detectors does not directly depend on particles energies;
- looks tempting the possibility to measure both energy and polarization of the beam by the same apparatus;
- use of different laser wavelengths will definitely help to control some of possible systematic uncertainties.

The weaknesses are:

- it is necessary to ensure equality of integrals of magnetic field for electrons with very different energies;
- the installation dimensions seems to be larger than one would like to have;
- three different types of coordinate detectors must work together to measure distances with high precision in absolute units.

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