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Precise beam energy measurement in collider experiments.

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Abstract

The methods of beam energy determination at actual colliders are reviewed.

Keywords: electron-positron collider, beam energy calibration, compton backscattering, resonance depolarization

1. Introduction

The high accuracy of e^+e^- colliders beam energy determination is crucial for a lot of physical studies:

- particles masses and widths measurements,
- study of interference effects in the cross sections,
- measurements of the cross sections themselves.

For example, the error of the measured Z-boson mass $m_Z = 91187.6 \pm 2.1$ MeV is dominated by the common LEP energy error 1.7 MeV [1]. At the low energy region in order to measure the $e^+e^- \to \pi^+\pi^-$ cross section below 1 GeV with accuracy about 0.5%, the beam energy should be measured with relative error $\delta E/E \sim 10^{-4}$.

In the simplest case the beam energy can be calculated as

$$E = \frac{B\rho}{\beta c} + \Delta_{cor}, \tag{1}$$

where B and ρ are magnetic field and beam radius of curvature, Δ_{cor} is a nonlinear correction. In this case the relative accuracy of the beam energy determination $\delta E/E$ is worse than 10^{-3}. The beam energy can also be determined by measuring the momentum of particles in collinear events. For example, in special case of the process $e^+e^- \to \phi(1020) \to K^+K^-$, the beam energy can been obtained with relative accuracy 5×10^{-5} at the ϕ-meson peak [2] as

$$E = \sqrt{p_K^2 + m_K^2} + \Delta_{cor}, \tag{2}$$

where p_K is an average momentum of K^+ and K^- mesons, m_K is the charged kaon mass, Δ_{cor} is a correction due to kaon ionization energy losses and due to emission of real photons. The beam energy can be calibrated using positions of the narrow and precisely measured resonances ($\omega, \phi, \psi, \Upsilon$).

Resonance depolarization (RD) method is the most precise and has relative error of about 10^{-6} [3]. Another possibility is the beam energy measurement using Compton back-scattering (CBS) of monochromatic laser radiation on the electron beam. In this case the relative accuracy is $10^{-4} - 10^{-5}$ [4].

2. Resonance depolarization method.

The beam energy determination using RD requires the polarized beam and is based on the coupling between the electron energy and frequency Ω of its spin precession during the motion of the particle in the transverse magnetic field with a revolution frequency ω_s:

$$E = \left(\frac{\Omega}{\omega_s} - 1\right)\frac{\mu_0}{\mu'} m_e c^2, \tag{3}$$

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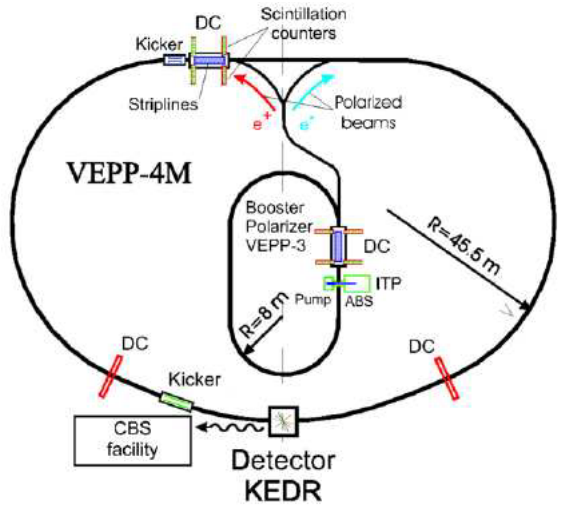

Figure 1: VEPP-4M layout.

where μ_0/μ' is the ratio of the anomalous and normal parts of the electron magnetic momentum known with a relative accuracy of 2×10^{-10} [1]. The frequency Ω can be obtained through resonant depolarization of the polarized beam due to an impact of an external electromagnetic field with such a frequency ω_d that

$$k\omega_s \pm \omega_d = \Omega(k \in \mathbb{Z}). \tag{4}$$

The beam is polarized due to the Sokolov-Ternov effect (radiation polarization)[5]: self-polarization of electrons moving in magnetic field for a long time through the emission of synchrotron radiation. The degree of polarization increase as

$$\zeta(t) = \frac{8}{5\sqrt{3}}\left(1 - e^{-\frac{t}{\tau_p}}\right), \tag{5}$$

where

$$\frac{1}{\tau_p} = \frac{5\sqrt{3}}{8}\alpha\left(\frac{\lambda_e}{\rho}\right)^3 \gamma^5 \omega_s. \tag{6}$$

The destruction of polarization is provided by a high frequency depolarizer. The moment of depolarization is detected by the process which cross-section depends on the polarization degree. For example, the cross section of intrabeam scattering (Toushek effect) of polarized electrons is smaller than for unpolarized ones:

$$d\sigma = d\sigma_0\left(1 - \zeta^2 \frac{sin^2\theta}{1 - 2cos^2\theta}\right). \tag{7}$$

Therefore, after depolarization the number of particles scattered out of the beam rises.

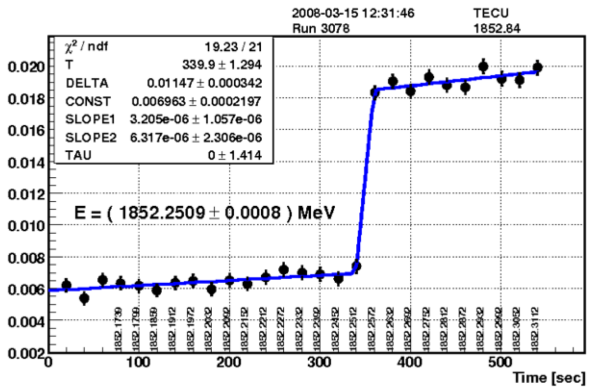

Figure 2: The ration of counting rates from polarized and unpolarized beams during depolarization.

The RD method was used for high precision measurements of the J/ψ, ψ', τ-lepton etc masses in experiments at collider VEPP-4M with KEDR detector [6, 7] (fig.1). In the energy range of charmonium the polarization time in the VEPP-4M is about 100 hours. Therefore the beam is polarized in VEPP-3M (booster of the VEPP-4M), where time of polarization is about 1 hour. The polarized beam is then injected in the VEPP-4M without significant depolarization. About 10 minutes later an unpolarized beam is added as a second bunch. The two matched striplines of the VEPP-4M kicker are used to create a TEM wave, which provide destruction of polarization. In order to detect the moment of depolarization the process of intrabeam scattering is used. The scattered electrons are detected using the polarimeter based on several groups of scintillation counters (they are marked as DC in fig.1), which can be moved inside the aperture in order to optimize the counting rate. Two electron bunches one being polarized and other not, which are moving one after another are used for calibration. The scattered electrons are detected from both beams. The ratio $1 - f_1/f_2$, where f_1 and f_2 are the counting rates of polarized and unpolarized beams respectively, shows a leap of about 2.5–3.5% at the moment of polarization destruction (fig.2.) The whole process of energy calibration by RD takes about 2 hours. The total error of a single measurement is about 2 keV. Between measurements the energy was interpolated taking into account various parameters related to VEPP-4M, e.g. guide field, temperature and etc. The interpolation accuracy in the most of J/ψ and ψ' scans did not exceed 5 keV. As a result the J/ψ and ψ' masses were measured with very high precision:

$$\begin{aligned} m_{J/\psi} &= 3096.900 \pm 0.006 \;\; MeV \\ m_{\psi'} &= 3686.099 \pm 0.010 \;\; MeV. \end{aligned} \tag{8}$$