A FAST POLARIMETER FOR e^+e^- STORAGE RINGS

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Abstract

A fast polarimeter for a precise measurement of transverse polarization of electron (positron) beam is presented. This polarimeter measures an asymmetry in the Compton scattering of circularly polarized laser beam on polarized electrons. The parameters of the laser polarimeter are discussed for study of beam polarization at the KEK TRISTAN main ring (MR) in the energy range of 25 - 32 GeV. A measurement of the beam polarization is expected to achieve a statistical accuracy of ±1 % in several seconds.

Introduction

In e^+e^- and ep physics experiments the role of polarized electron and positron beams are increasing with energy. Electrons (positrons) are transversely polarized anti-parallel (parallel) to the guiding magnetic field by the Sokolov - Ternov mechanism[1]. A natural polarization of electron beam has been observed in many storage rings[2] with energy less than 25 GeV. As energy increases it is expected that the degree of polarization becomes low due to strong depolarization effects. These are crucial problems to achieve high level polarized beams in high energy storage rings exceeding the 30 GeV range. The TRISTAN covers the energy range of 25 to 32 GeV, in which the study of beam polarization provides useful information.

A fast precision polarimeter is an essential tool to study polarization phenomena in e^+e^- storage rings. We have developed a fast polarization monitor to measure a transverse polarization of electron beam at TRISTAN MR, based on the Compton scattering of laser light on the electron beam. A fast data taking and an excellent precision are crucial points to measure a low level polarization with a short buildup time, expected in the MR. Features of our polarimeter design are to minimize a systematic error as well as a statistical error and to allow for measurement of the longitudinal polarization simultaneously.

Beam Polarization in TRISTAN

In the presence of depolarizing effects originating from magnetic field imperfections and misalignments in a real storage ring, the buildup of the beam polarization can be expressed in terms of the effective buildup time τ as

$$P_e(t) = \tau/\tau_p P_0(1 - \exp(-t/\tau)), \tag{1}$$

where P_0 is the ideal asymptotic polarization level, $P_0 = 8/(5\sqrt{3})$ = 92.38%, and τ_p is the natural polarization buildup time. The buildup time of the polarization for the beam energy E in GeV is given by

$$\tau_p = 98.66(\rho^3/E^5)(R/\rho)\,\text{sec}, \tag{2}$$

where ρ is the bending radius in meters and R is the machine mean radius. In the MR the natural polarization buildup time would be $\tau_p = 2.88 \times 10^9/E^5$ sec, typically 2 minutes for 30 GeV.

An observable buildup time depends on the asymptotic degree of the polarization determined by depolarization effects. The prediction of the polarization level can be calculated by a computer code SLIM[3]. Fig. 1 shows the expected polarization of the MR in the energy range 24 to 32 GeV, calculated with simulated magnetic field imperfections. This calculation takes no account of contributions from three large solenoids for the colliding detector. The absolute polarization level is expected to be very low around the depolarization resonance. It occurs when the spin tune $\nu = E/0.44065$ satisfies $\nu = n + n_x\nu_x + n_y\nu_y + n_s\nu_s$, where ν_x, ν_y, ν_s are the horizontal, vertical and synchrotron tunes, respectively and n, n_x, n_y, n_s are any integers. A polarization time will be 42 sec for a 30 % polarization level at 29 GeV in the MR.

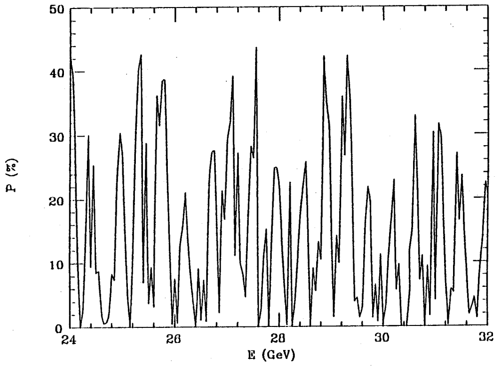

Fig. 1 The expected beam polarization of TRISTAN MR in the energy range of 24 to 32 GeV.

Compton Polarimetry

The laser polarimeter is a desirable tool to make a fast polarization measurement. The principle is based on the asymmetry in the Compton scattering of circularly polarized photons from a laser on an electron (positron) beam. A transversely polarized beam gives rise to an up-down asymmetry in the backscattered γ rate, depending on the left-right photon polarization. The differential Compton scattering cross section[4] of circularly polarized photons on transversely polarized electrons or positrons is written in the electron rest frame as

$$\begin{aligned} d\sigma/d\Omega = (r_e^2/2)(q/q_0)^2\,[(1+\cos^2\theta) + (q_0 - q)(1-\cos\theta) \\ \pm\, P_e P_\gamma \cos\phi(1-\cos\theta)q\sin\theta] \end{aligned} \tag{3}$$

where q_0 and q are the incoming and outgoing photon energies and θ and ϕ are the scattering angles. The kinematics and Lorentz transformation between the electron rest frame and the laboratory system are summarized using energies and momenta in units of electron rest mass:

$$\begin{aligned} q = q_0/[1 + q_0(1-\cos\theta)], \quad \gamma\tan\theta_L = \sin\theta/(1-\cos\theta), \\ q_0 \approx 2\gamma k_0, \quad k \approx \gamma q(\cos\theta - 1), \end{aligned} \tag{4}$$

where γ is Lorentz factor of the incident electron beam E/m_ec^2, k_0 and k momenta of the incoming and outgoing photons in the laboratory system, and θ_L the scattered photon polar angle with respect to the incoming electron beam direction.

In the laboratory system the maximum asymmetry of the backscattered γ rate occurs in the polar angles of $\theta_L \sim 1/\gamma$, typically 20 μrad in the TRISTAN energy range. The angular divergence of the beam and the angular resolution of the detector must be small compared to this angle so that the asymmetry of the γ ray angular distribution cannot be lost. The net angular resolution of the polarimeter with a rms position resolution Δ of the detector and a beam emittance ϵ is given by

$$\delta = \left\{(\epsilon/\beta)[1 + (\alpha - \beta/L)^2] + (\Delta/L)^2\right\}^{1/2} \qquad (5)$$

where L is the distance of the detector from the laser interaction point and α, β are the beam Twiss parameters at the interaction point. The parameters are chosen so as to minimize the angular resolution. This is optimized by choosing an interaction point where the β- function is its maximum value. Usually in the e^+e^- storage rings, the horizontal emittance is large enough to smear out an asymmetry of the projected profile on the detector. Therefore only vertical distribution of the γ rays is measured. The vertical β and α functions at the interaction point are 23.7 m and $\sim$ 0 m, respectively, and L is set to be 38 m because of restriction on the installation space. A typical vertical emittance is 2.5 nm for 25 GeV, assuming a 2 % of the horizontal one. The projected beam spot size on the detector is 0.46 mm. If we use the detector with the position resolution 126 μm, the net angular resolution is 12.5 μrad, sufficiently smaller than $1/\gamma$.

The degree of polarization P_e can be determined by the vertical asymmetry of the measured γ rate and the analyzing power A for 100 % photon polarization:

$$P_e = (1/A)(N_+ - N_-)/(N_+ + N_-) \qquad (6)$$

where N_+ and N_- are the numbers of γ events counted at a vertical position for the two photon helicities. The vertical distribution of γ rays is calculated by integrating over the horizontal distribution and the γ energy distribution. Taking into account the angular divergence of the incident beam with a Gaussian distribution, an expected vertical profile at the detector is obtained as shown in Fig. 2. Fig. 3 shows the vertical asymmetry for two beam emittances. The analyzing power is defined by the ratio of the spin-dependent term σ_2 of cross section to the non spin-dependent term σ_0. It depends on bins used in the asymmetry measurement and the cutoff γ energy. Since the accuracy of the polarization measurement is given by $\Delta P_e \sim 1/(A\sqrt{N})$ with $N = N_+ + N_-$, these values should be chosen so as to optimize the quantity of $A^2N \propto \sigma_2^2/\sigma_0$. The dependence of relevant quantities on the vertical bins used in the measurement is shown in Fig. 4.

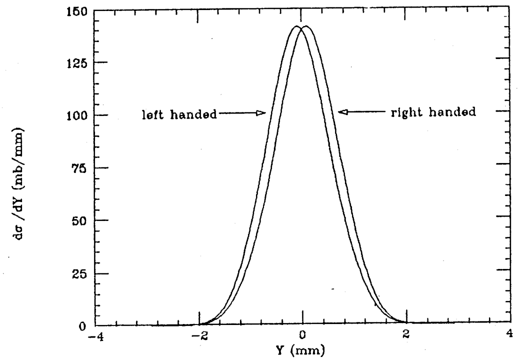

Fig. 2 The vertical distribution of γ rays at the detector.

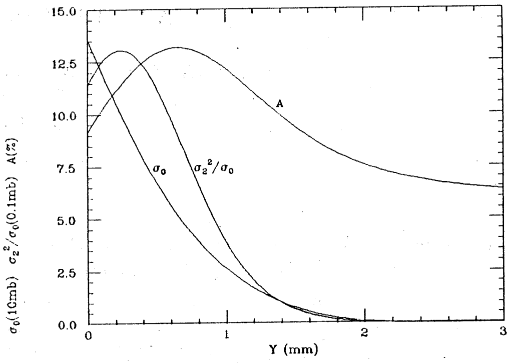

Fig. 4 The dependence of σ_0, σ_2^2/σ_0 and $A = \sigma_2/\sigma_0$ on the vertical position used in the measurement.

Laser Polarimeter

Two methods have been proposed to measure the vertical asymmetry of γ rays. In the single photon counting method[2] the electron beam is illuminated by a low power, high repetition rate laser pulse. Each backscattered photon is measured by the position sensitive detector and the calorimeter. The multi-photon technique[5] uses a high peak power laser to produce numerous γ rays per interaction. The number of photon is recorded as a deposited energy in the calorimeter. We adopted the single photon counting method to avoid systematic errors resulting from a drift of the closed orbit and a photon counting detector.

Laser

We use a cavity-dumped Ar ion laser producing the 514.5 nm (2.41 eV) line. The cavity-dumped pulses are synchronized with the beam revolution frequency to illuminate the electron beam at each crossing. The laser pulse has a width of 15 ns (FWHM) and a peak power of 50W. The linearly laser light is converted to either right or left circularly polarized light with a KD*P Pockels cell. The laser beam is guided through the transport optics consisting of 5 mirrors and a final focusing lens. The alignment of the laser beam is performed with the optical target remotely inserted at the interaction point. The laser beam is focused at this point with a rms spot size approximately 1 mm.

Experimental layout

The experimental layout for polarimetry is shown in Fig. 5. The laser beam is introduced from the laser building into the MR beam pipe and then deflected towards the interaction point where the laser light crosses the electron beam at an angle of 8 mrad in the horizontal plane. The backscatterted γ rays travel along with

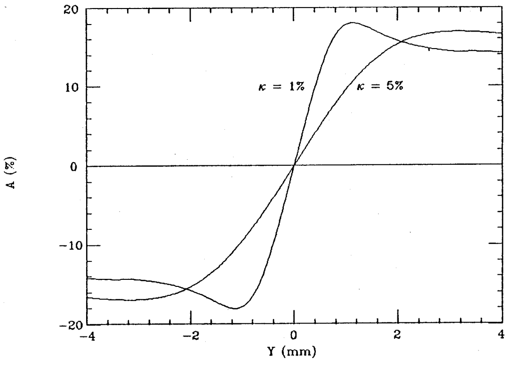

Fig. 3 The asymmetries at the detector for two beam emittances. The κ denotes a ratio ϵ_y/ϵ_x.

the electron beam, then leave the beam pipe at the end of the first main dipole and finally reach the γ detector located about 38 m downstream from the interaction point. Some modifications of the magnet and vacuum chamber have been worked out to make the path of the γ rays.

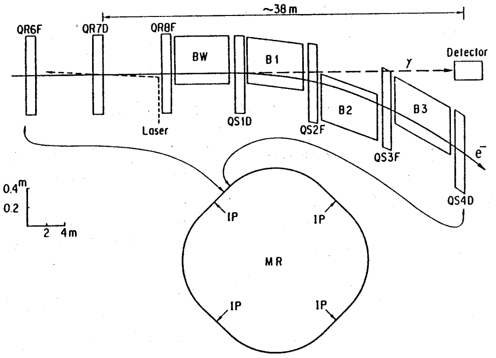

Fig. 5 The TRISTAN polarimeter layout.

γ detector

A schematic diagram of the γ detector is shown in Fig. 6. The detector has two functions for measurement of the position and energy distribution of γ rays. The photon trigger is provided by 3 scintillation counters S1, S2, S3 and a lead glass calorimeter. The counter S1 vetoes charged particles. A 2 mm thick ($\approx$ 0.6 r.l.) tungsten converter is followed by the trigger counters S2, S3 and the lead glass counter with $\approx$ 18 r.l. for the energy measurement of a $e^- - e^+$ pair created in the converter. The vertical position of a converted photon is determined from hit channels of the silicon microstrip detector (SSD) with a 50 mm×50 mm sensitive area. The SSD is composed of P-N junctions formed on a silicon substrate with 42 μm pitch. A capacitive charge devided pulse is read out every three strips. It is possible to detect a charged particle with position resolution of 42 μm. We use 160 readout channels over a 20 mm vertical width.

Pulse height signals generated in the SSD and the lead glass calorimeter are digitized by fast ADC CAMAC modules (LeCroy FERA) in coincidence with the trigger gate. A FERA ECL bus transfers encoded data to either of two 16K words memory module. Then data are read out through CAMAC bus by the computer each time a memory module is filled with data. This system allows for fast data acquisition at the maximum rate of 80 kHz.

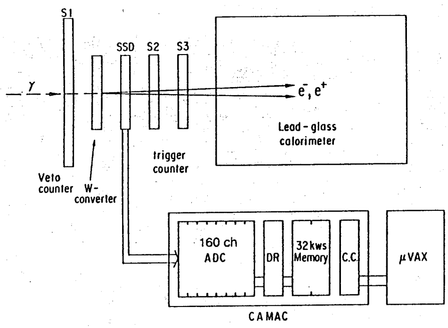

Fig. 6 The schematic diagram of the γ detector.

γ-Rate and Background

The luminosity of the electron beam- laser interaction with a horizontal crossing angle α is given by

$$\begin{aligned} L(\mathrm{kHz/mb}) &= 257.1 \mathrm{I_e W_L} \{\sigma_{\mathrm{ey}}^2 + \sigma_{\mathrm{Ly}}^2\}^{-1/2} \\ &\times \left\{\cos^2(\alpha/2)(\sigma_{ex}^2 + \sigma_{Lx}^2) + \sin^2(\alpha/2)(\sigma_{ez}^2 + \sigma_{Lz}^2)\right\}^{-1/2} \end{aligned} \tag{7}$$

where I_e is the electron beam current in A, W_L the laser energy per pulse in μJ, $\sigma_{ex}, \sigma_{ey}, \sigma_{ez}$ and $\sigma_{Lx}, \sigma_{Ly}, \sigma_{Lz}$ are the rms dimensions of the electron bunch and of the laser beam in mm. If a 1.88 μJ laser pulse with a round profile $\sigma_{Lx} = \sigma_{Ly} = 1$ mm collides the electron beam at an angle 8 mrad, the expected luminosity is 62.2 Hz/mb for a 1 mA TRISTAN beam. The total cross section of the Compton scattering is 385 mb for 2.41 eV photons on a 25 GeV electron beam. Thus an estimate of the backscattered γ rate is 24 kHz/mA.

The background for the Compton γ events is high energy γ rays produced from the gas bremsstrahlung. The total cross section of the bremsstrahlung in a gas with average atomic number Z=5 is given by $\sigma_{brem}(> k/E) = 57.3\{6.37[(k/E) - \ln(k/E)] - 2.34(k/E)^2 - 4.03\}$ mb, where k is the emitted photon energy and E is the electron beam energy. The γ rate from a 1 mA electron beam on the residual gas of a pressure $p \times 10^{-9}$ Torr in a 200 m MR straight section leads to $1.1p$ kHz/mA for $0.19 < k/E < 0.48$.

In a real measurement the bremsstrahlung background may become comparable to the Compton events. Its background can be subtracted from the collected data if we take only the backgrounds in the laser-off run besides the up -down asymmetry run. The polarization can be corrected with the background events N_B as

$$P_e = (1/A)(N_+ - N_-)/(N_+ + N_- - 2N_B) \tag{8}$$

where N_+ and N_- are the up and down asymmetry events including the background.

Conclusion

We have constructed a fast precision polarimeter for the e^+e^- TRISTAN main ring. The first polarization measurement in the 30 GeV range will be carried out with this polarimeter soon.

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