VECTOR POLARIMETER USING SYNCHROTRON RADIATION FOR LINEAR AND CIRCULAR ELECTRON COLLIDERS

I.P.Karabekov and S.I.Karabekian
Yerevan Physics Institute, 2 Alikhanian Brothers St., Yerevan, 375036 Armenia

1. ABSTRACT

A method and facility to measure the longitudinal and transverse polarization of an electron beam in a linear or circular accelerator using synchrotron radiation created by a three-pole high-field-intensity wiggler magnet is proposed.

Quantum theory predicts that a longitudinally polarized electron emits a slightly different number of synchrotron photons into the space above and below the orbit plane. According to the theory, the total intensity of synchrotron radiation depends on a degree of transverse polarization too.

The facility for simultaneous measurement of both longitudinal and transverse polarization uses two synchrotron radiation beams extracted from opposite field direction parts of the wiggler. Using these two beams we avoid the large source of statistical error connected with vertical motion of the beam at a longitudinal polarization measurement. By measuring a flux difference of these two beams, one can determine the degree of transverse polarization.

The analyzing power of the method calculated for CEBAF, HERA and LEP electron beam parameters is about two order of magnitude higher than that of the presently used Compton polarimeter.

2. INTRODUCTION

A simultaneously measurement of a degree of transverse and longitudinal components of an electron beam polarization in linear accelerators and colliders is highly important because of a sequence of focusing and bending magnets of the beam optics in combination with an orbit vertical displacement can rotate the polarization vector at interaction point in any direction.

For circular colliders this measurement permits to control a spin rotator as well as to compensate a sources of depolarization.

The standard polarimeters in high energy electron colliders are laser polarimeters [1,2]. In [3] a method to measure the degree of a beam longitudinal polarization using synchrotron radiation has been proposed. The method is based on the predictions of the quantum mechanical theory of synchrotron radiation from polarized electron developed by Sokolov and Ternov [4]. In this paper a vector polarimeter using synchrotron radiation generated by a special short dipoles is presented and its application to CEBAF, HERA and LEP are discussed.

3. PRINCIPAL CONSIDERATIONS

According to quantum mechanical description of synchrotron radiation a longitudinally polarized electron emits a slightly different number of synchrotron photons into the space above and below the bending plane. A total photon flux emitted by a transverse polarized electron in the magnetic field parallel and antiparallel to a spin vector are also different. In this paper these two phenomenon are proposed for the measurement of spin vector direction. The angular and spectral distributions of the intensity of the σ and π polarized synchrotron radiation emitted from an electron with arbitrary spin direction can be calculated by the following formula:

$$W_{\sigma,\pi} = \frac{27}{16\pi}\frac{ce_0^2}{R^2 e_0^{9/2}}\int_0^\infty \frac{y^2 dy}{(1+\xi y)^5}\oint \Phi_{\sigma,\pi} d\Omega, \qquad (1)$$

where $\Phi_{\sigma,\pi}$ describes the angular and spectral distribution of the radiation. For longitudinally polarized electrons these functions (neglecting spin-flips caused by synchrotron radiation) are:

$$\Phi_\sigma = \frac{1+\xi y}{3\pi^2\gamma^4}(1+\alpha^2)^2 K_{2/3}^2(z) \left(1+\varsigma\xi y\frac{\alpha}{\sqrt{1+\alpha^2}}\frac{K_{1/3}(z)}{K_{2/3}(z)}\right) \qquad (2)$$

$$\Phi_\pi = \frac{1+\xi y}{3\pi^2\gamma^4}\alpha^2(1+\alpha^2)^2 K_{1/3}^2(z) \left(1+\varsigma\xi y\frac{\sqrt{1+\alpha^2}}{\alpha}\frac{K_{2/3}(z)}{K_{1/3}(z)}\right) \qquad (3)$$

where ζ is the electron polarization, $\varepsilon_0 = 1-\beta^2$, $z = \frac{\omega}{2\omega_c}(1+\alpha^2)^{3/2}$, $\omega_c = \frac{3}{2}\omega_0\gamma^3$, $\omega_0 = \frac{c}{R}$, c is the speed of light, R is the bending radius, $\gamma = \frac{E}{m_0 c^2}$, e is electron charge , $y = \frac{\omega}{\omega_c}$, $\alpha = \gamma\psi$, ψ is the vertical angle between the orbit plane and the direction of the radiated photons, θ is bend angle, $K_{1/3}(z)$ and $K_{2/3}(z)$ are modified Bessel functions, $\xi = \frac{3}{2}\frac{H}{H_0}\frac{E}{m_0 c^2}$, and $H_0 = 4.41 \times 10^{13}$Oe.

In the case of transverse spin polarization (2) and (3) must be replaced by:

$$\Phi_\sigma = \frac{1+\xi y}{3\pi^2\gamma^4}\left(1+\alpha^2\right)^2 \left(1+\varsigma\frac{\xi y}{\sqrt{1+\alpha^2}}\right)\frac{K_{1/3}(z)}{K_{2/3}(z)}K_{2/3}^2(z) \quad (4)$$

$$\Phi_\pi = \frac{1+\xi y}{3\pi^2\gamma^4}\alpha^2\left(1+\alpha^2\right)K_{1/3}^2(z) \quad (5)$$

If we combine equations (1) with (2),(3) and with (4),(5), and assume ξy << 1 the angular distribution of the power radiated by n_e electrons into the solid angle $d\psi d\theta$ for a given photon frequency, y, have to be received [3]. For calculations it is convenient to convert the formulas for radiated power, $W_{\pi,\sigma}$, into formulas for photon numbers, N_g,by dividing (1) by the photon energy $\varepsilon_\gamma = \frac{3}{2}\frac{\hbar c}{R}\gamma^3 y$. Taking into account that $e_0^2/\hbar c = 1/137$ and $n_e = 2\pi R I_e / e_0 c$ where I_0 is beam current, replacing $d\theta$ by finite horizontal angle $\Delta\theta$ and $d\alpha = \gamma d\psi$, the total number of emitted photons, $N_{\gamma(long.)}$, by longitudinally polarized beam and the number of photons in the flux difference emitted in to the space above and below the orbit plane can be presented as follows:

$$N_{\gamma(long.)} = \frac{3}{4\pi^2}\frac{1}{137}\frac{I_e}{e_0}\gamma\Delta\theta\int_{y_1}^{y_2}\int_{-\alpha}^{+\alpha} y\left(1+\alpha^2\right)^2 \left[K_{2/3}^2(z) + \frac{\alpha^2}{1+\alpha^2}K_{1/3}^2(z)\right]dy d\alpha, \quad (6)$$

$$\Delta N_{\gamma(long.)} = \frac{3}{\pi^2}\frac{1}{137}\frac{I_e}{e_0}\xi\varsigma\gamma\Delta\theta\int_{y_1}^{y_2}\int_0^{\alpha} y^2\alpha\left(1+\alpha^2\right)^{3/2} K_{1/3}(z)K_{2/3}(z)dy d\alpha. \quad (7)$$

The total number of photons radiated by transverse polarized beam can be presented as:

$$N_{\gamma(trans.)} = \frac{3}{4\pi^2}\frac{1}{137}\frac{I_e}{e_0}\gamma\Delta\theta\int_{y_1}^{y_2}\int_{-\alpha}^{+\alpha} y\left(1+\alpha^2\right)^2 \left[\left(1-\zeta\frac{\xi y}{\sqrt{1+\alpha^2}}\frac{K_{1/3}(z)}{K_{2/3}(z)}\right)K_{2/3}^2(z) + \right. \left. + \frac{\alpha^2}{1+\alpha^2}K_{1/3}^2(z)\right]dy d\alpha. \quad (8)$$

The sign of ζ depends on spin direction: (-) is for parallel and (+) for antiparallel to vector of the magnetic field. Therefore the flux difference of two SR beams emitted from transverse polarized electrons in two opposite field direction bending magnets is proportional to degree of polarization and can be presented as followings:

$$\Delta N_{\gamma(trans.)} = \frac{3}{2\pi^2}\frac{1}{137}\frac{I_e}{e_0}\xi\varsigma\gamma\Delta\theta \int_{y_1}^{y_2}\int_{-\alpha}^{+\alpha} y^2\left(1+\alpha^2\right)^{3/2} K_{1/3}(z)K_{2/3}(z)dy d\alpha. \quad (9)$$

The analyzing power of the proposed polarimeter have to be calculated as follows:

$$P = A\sqrt{2N_{\gamma(l,t)}}, \quad (10)$$

where A is asymmetry

$$A = \frac{\Delta N_{\gamma(l,t)}(\varsigma)}{N_\gamma(l,t)}. \quad (11)$$

4. THE SOURCES OF UNCERTAINTIES AND MEASURING TECHNIQUE

According to above developed method the polarimeter is consists of two opposite field direction magnets generating two SR swaths and a detectors for photon flux difference measurement. To avoid of beam orbit distortion these magnets have to be a part of a three-pole wiggler. The photon flux differences can be measured by air or heavy gas (Kr or Xe) filled differential ionization chamber (DIC) for an accelerators of energy up to 10 GeV (CEBAF) generating the SR in x-ray bandwidth. For energy region of HERA, LEP and SLC the scintillator or Cherenkov counters will be more effective.

The dominant source of systematic uncertainties for longitudinal polarization measurement is an electron beam vertical displacement. This error can be compensated using two SR swaths generated in bending magnets with opposite field direction. The main idea, which is easy to explain in a case of ionization chamber (See Fig. 1), is as follow: the vertical displacement of SR beams in (DIC) have equal value and the same direction, while the flux asymmetry cause by longitudinal polarization have an opposite sign.

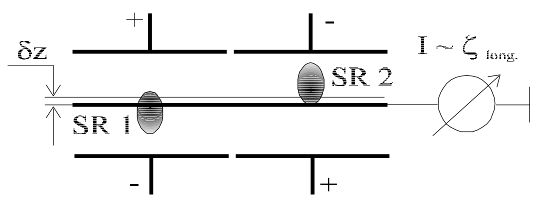

Figure 1. Compensation of SR beams vertical displacement, δz, by four electrodes DIC.

Two SR beams (SR1 and SR2) crosses the DIC having common gathering electrode and four high-voltage electrodes (HVE). The high voltage for each pair of electrodes is the same but the voltages has opposite sign.

The electric field created by each pair of (HVE) in ionization chamber has opposite direction too. Therefore the vertical displacement of the swaths must be fully compensated and the gathered charge is proportional to the degree of longitudinal polarization only. The transverse polarization according to (9) have to be measured as a difference between the photon fluxes generated in the magnets having opposite field direction. The differential ionization chamber having two HVE and common gathering electrode have to be used (See Fig.2).

5. THE CALCULATIONS

The results of calculation of the N_γ and $\Delta N_{\gamma(l,t)}$ in 2 T wiggler having pole length L_{wg} and consequently the asymmetry A, and the analyzing power ,P, for CEBAF, HERA and LEP are presented in Table 1.

Table 1.

CEBAF	E = 4 GeV I = 100 μA B_{wg} = 2 T L_{wg} = 6.6 cm	N_γ= 9.85×10^{13} $\Delta N_{\gamma l}$= 3.2×10^{8} $\Delta N_{\gamma t}$= 9.1×10^{8}	A_l=0.33×10^{-5} A_t=0.92×10^{-5} P_l=32.26 P_t=92.1
HERA	E = 27.5 GeV I = 20 mA B_{wg} = 2 T L_{wg} = 5 mm	N_γ= 1.18×10^{15} $\Delta N_{\gamma l}$= 3.0×10^{10} $\Delta N_{\gamma t}$=8.5×10^{10}	A_l= 0.25×10^{-4} A_t= 0.72×10^{-4} P_l= 8.7×10^{2} P_t= 2.5×10^{3}
LEP	E = 45 GeV I = 10 mA B_{wg} = 2 T L_{wg} = 7.5 mm	N_γ= 1.1×10^{15} $\Delta N_{\gamma l}$= 4.0×10^{10} $\Delta N_{\gamma t}$= 1.2×10^{11}	A_l= 0.37×10^{-4} A_t= 1.03×10^{-4} P_l= 1.22×10^{3} P_t= 3.43×10^{3}

According the Table 1. the analyzing power of SR polarimeter is more higher of the same parameter of laser polarimeter for both low and high energies accelerators.

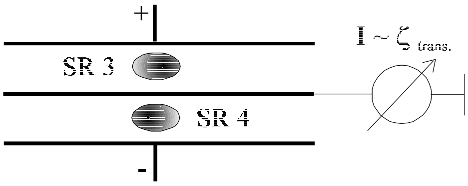

Figure 2. The transverse polarization measurement.

6. QUANTUM DEPOLARIZATION CAUSE BY WIGGLER

The quantum depolarization build-up time τ_{dep} cause by the wiggler field ($B_{wg} \times L_{wg}$) can be estimated as [2]:

$$\tau_{dep}(\sec) = 98.66 \frac{\rho^3_{wg}(\mathrm{m})}{E^5(\mathrm{GeV})} \frac{2\pi R}{L_{wg}} \ , \qquad (12)$$

where ρ_{wg} and L_{wg} are accordingly bending radius and total pole length of the wiggler and R is mean radius of the storage ring. According to (12) τ_{dep} for HERA (R = 1000 m, L_{wg}= 5 mm) is about 55 hours and the degree of beam polarization will decrease by about 0.5 %.

The schematic view of vector polarimeter for CEBAF case is presented in Figure 3.

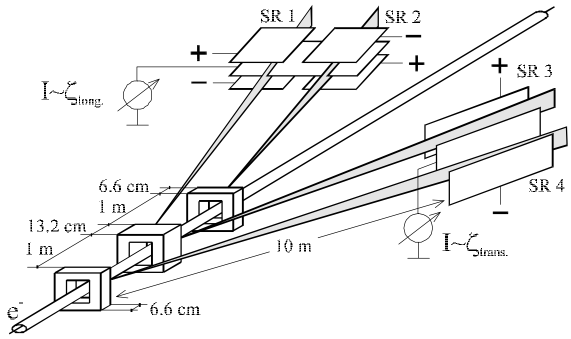

Figure 3. The schematic view of vector polarimeter.

7. ACKNOWLEDGMENT

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