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POLARIZATION MEASUREMENTS

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A b s t r a c t

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1 Abstract

Polarization monitors are an essential tool for the commissioning and operation of those accelerators where polarized beams are required. Experiments with polarized beams were suggested for many accelerators : For electrons/positrons as well as protons machines, for beams with an energy of some hundred MeV up to TeV colliders such as the SSC and future linear colliders. In this paper some aspects of the accelerator physics with polarized beams are discussed. Then an overview of various types of polarimeters is given. A more detailed description of the LEP polarimeter follows and the paper will conclude with a presentation of some results from the LEP 1991 run.

2 Introduction

The degree of polarization is defined as : $P = (N_1 - N_2)/(N_1 + N_2)$ with N_1 the number of particles with the spin parallel to a given direction, and N_2 the number of particles with the spin in the opposite direction. For an ensemble of particles the classical equations of motion for a magnetic moment $\vec{\mu}$ can be used to describe the spin motion [1]. The rotation of a magnetic moment of an electron in a magnetic field is given by the BMT equation [2] (the electric field is not considered) :

$$\frac{d\vec{\mu}}{dt} = -(e/\gamma mc^2)((1+a)\vec{B}_{\parallel} + a\gamma\vec{B}_{\perp}) \times \vec{\mu} \quad (1)$$

γ is the relativistic factor, a is the anomalous magnetic moment for electrons or positrons, $\vec{B}_{\parallel}$ and $\vec{B}_{\perp}$ the component of the field parallel and orthogonal to the particle momentum. For protons a is replaced by G , with G the anomalous magnetic moment for protons.

We assume a particle travelling in a magnetic field and deflected by the angle α . If the polarization vector is orthogonal to the magnetic field it will rotate around the field axis by an angle $\gamma a \alpha$ for electrons and positrons, and by $\gamma G \alpha$ for protons.

For high energy electron positron storage rings like LEP the spin rotates much faster than the particle. At an energy of 46.5 GeV the number of spin turns for one revolution, the spin tune, is $\gamma a = 105.5$.

3 How to get polarized beams

Protons : sources of polarized protons with a polarization level up to 100 % are available [3]. During the acceleration process the polarization has to be conserved.

Because of the presence of many depolarizing resonances the optimization of the machine to operate with polarized beams is a lengthy and tedious process.

Antiprotons : polarized antiproton beams are not yet available. However, a proposal to polarize antiprotons in a storage ring was made [4].

Electrons : for Linacs and Synchrotrons polarized beams have been accelerated at various machines. A polarized source is required, the polarization level of the sources in use is limited to about 50 % [7]. New types of sources with higher level of polarization are still limited in beam current. The acceleration in linacs is easier than in synchrotrons because no or only small deflecting magnetic fields act on the spin. For electron synchrotrons similar techniques to accelerate polarized particles are necessary as for proton synchrotrons.

For e+e- storage rings the phenomenon of self polarization by the so-called Sokolov-Ternov effect is well known [5]. The polarization level increases exponentially to a maximum possible level of 92.4 % if no depolarizing effects are present. The polarization direction is parallel to the magnetic field. The time constant is $\tau = 1.63(R/\rho)\rho^3/E^5$ with R the average radius and ρ the dipole bending radius [1]. For DORIS at 5 GeV/c: $\tau = 5$ min, for LEP at 46 GeV/c: $\tau = 300$ min.

4 Depolarizing mechanisms

In a circular accelerator depolarizing resonances are always present. It is well known that to operate a machine betatron resonances have to be avoided in order not to loose the beam. For the operation with polarized beams the situation is similar : the spin tune must not be an integer value. Not only integer resonances have to be considered, in general the resonance condition for resonances which might lead to depolarization is :

$$\gamma a = k + lQ_x + mQ_z + nQ_s \quad (2)$$

k,l,m,n are integer values and Q_x, Q_z, Q_s the betatron tunes. The integer resonances $\gamma a = k$ appears all 440.65 MeV/c for electrons and positrons (for protons a must be replaced by G).

In the following some examples of polarization measurements are given.

- At the Brookhaven AGS polarized protons were accelerated to 22 GeV/c. Fig.1 shows the optimization of the machine during a period of 3 weeks. Polarized particles are injected and accelerated to a momentum of 6 GeV/c. The depolarizing resonances were compensated until a polarization level of 80 % was achieved. Then the momentum ramp was increased to accelerate the particles to 8.6 GeV/c and the polarization again optimized. After three weeks of continuous optimization a polarization level of 45 % was achieved at a momentum of 18.5 GeV/c.

Figure 1: Optimization of the Polarization in the Brookhaven AGS [6]

- A very nice illustration of the existence of depolarizing resonances comes from SPEAR [9]. The polarization level was measured as a function of the momentum between 3.52 GeV/c and 3.76 GeV/c (fig.2). Around the integer spin resonance $\gamma a = 8$ no polarization was observed. Between the resonances the polarization level was close to the maximum possible level of 92.4 %. In between many depolarizing resonances were seen. Most of them can be clearly identified using eq.2. The strongest resonances are : $\gamma a = n - Q_y$ and $\gamma a = n - Q_x$.

Figure 2: Polarization level as a function of machine energy at SPEAR [9]

- Table I shows a list of electron positron storage rings where beam polarization was measured. In all machines with lower energy a high level of polarization has always been observed. At PETRA a polarization level of 80 % was achieved at a momentum of 16.5 GeV/c after applying corrections which

reduced the strength of the most important depolarizing resonances. At 21.5 GeV/c the level of polarization did not exceed 40 %. At LEP the maximum level is about 16 %. TRISTAN reported a polarization level of 40 % and it was observed that the polarization axis was tilted, therefore a longitudinal component was measured. This is a surprising result, because one expects the polarization to be parallel to the magnetic field.

TABLE I : Observed polarization level and polarization time constant for various electron positron colliders [13, 12, 24]

Machine	Energy [GeV]	τ_p [min]	Polarization in %
VEPP	0.65	70	80
ACO	0.53	160	90
VEPP-2M	0.65	60	90
SPEAR	3.7	15	70
VEPP-4	5	40	80
DORIS	5	4	80
CESR	5	300	80
PETRA	16.5	18	80
PETRA	21.5	5	less than 40
TRISTAN	30.0	2	40
LEP	46.5	300	15

The polarization level can be calculated to first order with the computer code SLIM [10]. Although various effects such as energy spread and nonlinear resonances are not considered, the program gives a useful indication of the polarization behavior. For LEP, the results of a simulation are shown in fig.3. An improved polarization optics was assumed and the known imperfections such as orbit deviations, coupling and spurious vertical dispersion were taken into account. The expected polarization level for a spin tune of 105.5 was about 20 %. Repetitive measurements of the polarization at this momentum have been done, a polarization level between 5 and 16 % has been observed during different runs.

It has been always observed that the polarization level is high for small machines, whereas for machines of the size of LEP and TRISTAN the level is low. To obtain a high level of polarization in these colliders optimization procedures are mandatory.

To operate future proton colliders such as LHC and SSC with polarized beams polarized particles have to be injected. Since more than thousand depolarizing resonances are crossed during the acceleration process insertions like Siberian snakes [11] will be required to maintain the polarization of the injected beam.

To operate an accelerator with polarized beams sophisticated instrumentation is required : The need for a polarimeter which measures the polarization as fast

Figure 3: Polarization level from a simulation expected for LEP as a function of the spin tune [8]

as possible is obvious. Many depolarizing mechanisms strongly increase with increasing vertical rms closed orbit. A powerful closed orbit measurement and correction scheme is therefore required. For LEP the rms value of the vertical closed orbit is about 0.7 mm. It is doubtful if a much better precision, say 0.2 mm, can be achieved in an accelerator of 27 km length.

5 Polarization as a tool

To operate an accelerator with polarized beams is difficult and requires both money and manpower. This can be justified by :

- The interest of the high energy physics community to perform experiments with polarized beams.
- The precision calibration of the energy of the beam particles in electron positron storage rings.

Whereas high energy physics experiments require in general longitudinally polarized beams with a polarization level of more than 50 %, the energy calibration can be done with transverse polarization of some percent.

6 Energy Calibration

An energy calibration of the beams is of interest in order to precisely measure the mass of particles as Υ' , Z_0 and many others. Fig.4 shows a result from DORIS. The cross section for the Υ' is shown as a function of the center of mass energy (which is twice the particle energy). A precise knowledge of the beam energy is needed to measure the particle mass. In particular for LEP this is of great interest to measure the mass of the Z_0 resonance as well as its width. Different methods have been employed to measure the absolute energy :

- The measurement of the magnetic fields in a reference magnet. This method is limited to a precision of about $\delta E/E = 10^{-3}$.

Figure 4: Cross section of the Υ' resonance measured at DORIS [16]

- At LEP the beam momentum has been calibrated using protons [14]. Protons are circulating along the same trajectory as positrons at injection with about 20 GeV/c. Whereas the positron speed is very close to the speed of light with $\gamma = 40000$, the protons are not highly relativistic ($\gamma = 20$). A measurement of the speed difference between the positrons and protons gives the beam energy with a precision of about 10 MeV.
- Depolarization of the beam by applying an external magnetic field [15]. The spin tune is given by $\gamma a = \bar{\gamma} \bar{a} + n$, with $\bar{\gamma} \bar{a}$ the noninteger part of the spin tune. The integer n is known by the approximate knowledge of the energy from magnetic field measurements. To depolarize the beam a time dependent magnetic field in the horizontal plane is applied. If the frequency of the field is in phase with the spin rotation frequency around the main dipole field, the spin is rotated around the depolarizer field axis in a resonant way. The rotation leads either to depolarization or to a spin flip. Both cases have been observed. The γ factor and therefore the energy can be simply calculated by:

$$\gamma = \frac{f_{dep}/f_{rev} + n}{a} \quad (3)$$

with f_{rev} the revolution frequency and f_{dep} the frequency of the depolarizing magnetic field. In fig.5 the polarization level as a function of the depolarizer frequency for DORIS is shown [16]. Below and above the resonance no depolarization is observed. The resonance width depends on the strength of the depolarizing field and can be as small as $\delta E/E = 10^{-5}$ which determines about the limit of this method for energy calibration.

7 Polarimeter : Generalities

Within this report it is not possible to describe all types of polarimeter in detail. Therefore I discuss some general principles common to most polarimeter designs. Then a more detailed description of polarimeters for electrons and positrons follows.

Figure 5: Example of a depolarization curve. Horizontal error bars indicate the sweep range of the frequency generator [16].

All polarimeters are based on the electromagnetic or strong interaction of the polarized beam particles with a "target". The target might be another beam or a piece of material. In some designs the target needs to be polarized. Either the scattered beam particles, the target particles or both are detected (see fig.6).

Figure 6: Typical layout of a polarimeter

In the LAB system the particles scattered under an angle θ are detected. The detector measures either the number of particles or the deposited energy. If the beam is polarized the signal is different for detector 1 and detector 2. The polarization level is given by :

$$P = 1/A \times \frac{N1 - N2}{N1 + N2} \quad (4)$$

with A the analyzing power of the polarimeter, N_1 and N_2 the number of particles or the deposited energy in the detectors. Another possibility is to use only one detector and to measure the differences for positive and negative beam polarization.

Another important quantity is the cross-section for a given scattering process. The larger the cross section, the more particles are scattered. The precision of the measurement is usually limited by statistics, therefore a high rate reduces the time for a measurement. A common problem are possible systematic errors. If detector 1 and detector 2 have different sensitivities even with a nonpolarized beam a signal as expected from a polarized beam is measured. To reduce systematic errors it is common to change the direction of either beam or target polarization. Another estimate of the systematic errors is to measure with unpolarized beams.

In Table II various types of scattering processes in polarimetry are shown. For electron positron polarimeter Møller, Compton and Mott scattering have been used. All cross sections can be calculated analytically with QED. They are valid in a wide energy range. E.g. Møller polarimeter were used for beams with a momentum of some 100 MeV/c up to 50 GeV/c. In high energy physics experiments polarization is observed as well due to the dependence of the cross section for many processes for particle production on the beam polarization [17]. In general these effects are not adequate for polarimetry because the cross sections are too small.

TABLE II: Polarimeter for Electrons [7] [20] [19] [26] and Protons [18]

Polarimeter for electrons Target	Effect	Comments
circular polarized light	Compton scattering	A some 10 % at LEP
polarized e- in ferro-magnetic target	Møller scattering	A about 6 % at SLC
High Z nucleus	Mott scattering	few eV to some 100 keV
polarized e- in the same bunch	Møller scattering (Touschek effect)	less than 1 GeV
positrons in e+e- colliders	different effects	
Polarimeter for protons		
protons in CH ₄ or Carbon	p-p elastic scattering	classical method to some 10 GeV
high Z nucleus (Pb)	Primakoff effect : $p+Z = p+\pi+Z$	for high energies
scintillating target	Coulomb-nuclear interference	for high energies

For most proton polarimeters effects based on QCD are used. No analytic calculation of the cross section can be done. Proton-Proton scattering is cited to be the classical method for measuring the polarization but is limited to a beam momentum of some 10 GeV/c [18]. Other techniques are under development, but for the time being they are medium size high energy physics experiments and not adequate for polarimeters built within beam instrumentation groups.

8 Electron-Positron Polarimeter

Møller polarimeter : They have been used to measure the polarization in Linacs and Synchrotrons [21, 19, 20]. Møller polarimeters are destructive for the beam: The beam hits a ferromagnetic foil in a magnetic field of some 100 G. The e- polarization in the target is about 0.08. In the cms system the asymmetry is maximum for scattering angles of $\theta = 90^\circ$ (fig.7). In the LAB system two electrons with half the beam momentum are observed at an angle of $90^\circ/\sqrt{\gamma}$. For the SLC the angle is about 5 mrad. Fig.8 shows a measurement done at SLAC : The Møller peak sits on the background from Electron-Fe Mott scattering. The asymmetry was measured with only one detector by reversing the beam polarization.

At the BONN synchrotron two detectors were used in coincidence which largely reduced the background from Mott scattering [19].

Figure 7: Principle of Møller polarimeter

Figure 8: Møller polarimeter : Results from SLAC [21]

Compton polarimeter : Circular polarized light is scattered off the beam. This technique is nondestructive and therefore used to measure the beam polarization in storage rings. In the rest system of the electron the asymmetry is maximum for scattering angles of about 90° .

Figure 9: Principle of Compton scattering

In the LAB system the photons are scattered into a narrow cone around the electrons with an opening angle of $\theta = 1/\gamma$, for LEP at 46.5 GeV/c this angle is $10 \mu\text{rad}$ (see fig.9). Because of the energy transfer of the electron to the photon the momentum of the photon is in the order of the momentum of the beam particles. The photons are detected downstreams after some 10 ... 100 m. The rms width of the vertical distribution is about $(1/\gamma) \times L$, with L the distance to the detector.

At LEP the "mean shift" δy between the distributions of scattered light with positive and negative helicity is observed (fig.10). δy is proportional to the level of polarization, for a fully polarized beams $\delta y = 500 \mu\text{rad}$ (for LEP with a beam momentum 46 GeV/c [22]).

The polarized light comes from a laser or from the synchrotron radiation as done in Novosibirsk [23]. Most polarimeter use lasers. A laser polarimeter has the following parts :

- Laser and optical system to generate circular polarized light.
- A system to transport the laser light to the electron beam, including mirrors etc.
- The scattered photons travel to the detector. In the first deflecting magnet after the interaction region the electrons and photons are separated. A sufficient aperture and a window for the traversal through the vacuum chamber for the photons travelling to the detector is required.

Figure 10: Measurement of the 'mean shift' in Compton polarimeter

- Detector to measure the spatial distribution of the scattered photons.
- Data acquisition and trigger system.

Single versus multiphoton technique :

In the single photon technique a continuous laser or a laser with a repetition frequency of the bunch frequency is used. The laser power is with some 10 W relatively low. Each bunch is illuminated. For one bunch the probability to scatter a photon is much less than 1 in order to avoid multiple scattered photons. Compton scattered photons cannot be distinguished from background photons from Gasbremsstrahlung. Photons in a given energy range are counted for left and right circular polarized light. The analyzing power is large, for LEP some 10 %, but might be reduced by background.

The multiphoton technique uses a laser with a low repetition frequency, but a high peak power (e.g. a Nd-YAG laser with 30 Hz repetition frequency, 10 ms long pulses of some 10 MW peak power).

Many photons per laser shot are scattered and the total energy for one shot is much larger than the beam particle energy (for LEP 100 - 1000 photons are scattered with a total energy of some TeV for each laser shot). The deposited energy is measured for left and right polarized light. An energy cut on single photons cannot be applied. The technique is insensitive to background, but the analyzing power is slightly lower than the single photon method (if the background for the single photon method is not considered).

To compare single and multiphoton polarimeter it is useful to calculate the number of scattered photons N_γ : $N_\gamma \propto P_{laser} N_{bunch} f$, with $f = \max(f_{bunch}, f_{laser})$. For LEP the number of photons is 200 time larger for the multiphoton polarimeter compared to the single photon polarimeter (4 bunches are assumed, $P = 30W$ for the single photon technique and 10 MW for the multiphoton technique).

9 The LEP polarimeter

Requirements for the LEP polarimeter :

- The expected level of polarization before the application of specific correction schemes is low : 3-20 % . With 3 % polarization the mean shift is about 15μ . Any systematic errors should therefore be less than 5μ in order to detect a level of 3 % with 3 sigma standard deviations.
- The degree of polarization should be measured as fast as possible. This is of particular importance for optimization of the polarization to measure as fast as possible if the polarization increases or decreases after changing a machine parameter.
- To synchronize the polarization measurement with the activities in the control room the polarimeter which is 2 km away must be remotely controllable.

Layout : The 60 mJ (compared to 90 mJ design value) light pulses from a 30 Hz Nd-YAG laser operated in the visible range at 532 nm and installed in an optical laboratory 15 m away from the LEP tunnel are guided towards the roughly evacuated beam pipe including three lenses and five multilayer dielectric mirrors (see fig.11) [24]. The light is polarized in a section with optical instruments installed on a bench at the laser output. A rotating $\lambda/2$ plate and a $\lambda/4$ plate can produce linear or circular light.

Figure 11: General layout of the LEP Compton polarimeter [24]

The final deflection onto the e- beam under an angle of 2-3 mrad is provided by (Ag + MgF₂)-coated CU mirror. Their position can be remotely adjusted. The high energy scattered γ 's reach the detector 247 m downstream the interaction point through a $50 \times 20 \text{ mm}^2$, 2 mm thick Al-window built in the modified

vacuum chamber in the main dipole about 225 m from the interaction point. A silicon calorimeter is employed to measure the distribution of the recoil photons (see fig.12). Four strip detectors ($S_1 - S_4$) and five unsegmented pads ($F_1 - F_5$) are inserted between tungsten plates. The 40 mm $\times$ 40 mm strip detectors have 16 horizontal strips with 2 mm pitch. A movable lead absorber is installed in front of the silicon calorimeter to shield the detector against synchrotron radiation. An absorber thickness of 0 - 5 radiation lengths can be selected according to the intensity of the synchrotron radiation.

The asymmetry function is defined as :

$$A(y) = \frac{n_r(y) - n_l(y)}{n_r(y) + n_l(y)} \quad (5)$$

where $n_{r,l}(y)$ are the γ rates at the vertical position y for right and left circular polarized light, or horizontal and vertical polarized light. The measured asymmetries are shown in fig.13, with circular polarized light as well as with linear polarized light. The asymmetry function is derived from distributions as shown in the fig.13. For linear polarized light the rms width of the distribution changes significantly independent of any beam polarization when changing from horizontal to vertical polarization. In first order the mean of the distribution does not move and the mean shift δy is zero. With circular polarized light and beam polarization the mean of the distribution changes.

Sources for systematic and statistical errors are :

- A jitter of the e- beam orbit. This leads to displacements of the backscattered photon beam.
- If the aperture for the scattered photons is limited, the tails of the photon distribution might be lost. If the light is perfectly circular polarized, the distributions for right and left circular polarized light are identical if the beam is not polarized. If the light has some linear component the width of the distribution changes. This change together with the limited aperture can lead to a mean shift independent of polarization.
- Nonlinearities of the detector.

Although these effects are small, an optimization is needed to avoid any mean shift larger than a few μm :

- Minimization of the linear polarization component in the light.
- Precise centering of the backscattered photons in the aperture.

Figure 12: Silicon Strip calorimeter as a detector for the LEP polarimeter

- All systematic errors due to electron orbit jitter are minimized by reversing the light helicity from one laser shot to the next.

10 Results from LEP

Fig.14 shows the measured mean shift as a function of time [28] [29] [31]. The initial value is about $45 \mu\text{m}$. To ensure that the mean shift is due to beam polarization vertical closed orbit bumps are applied generating a depolarizing resonance which is expected to totally destroy the polarization. The systematic effects are then minimized and a mean shift of about zero is observed. After switching off the closed orbit bumps the polarization builds up with the time constant τ .

The polarimeter measures the mean shift δy . To calculate the degree of polarization from the mean shift two methods were employed :

- From Monte Carlo simulations the expected mean shift for a polarization level of 100 % is $500 \mu\text{m}$ for a beam momentum of $46.5 \text{ GeV}/c$. The polarization level is given by : $P = \delta y[\mu\text{m}]/500$.
- Another method is a three parameter fit of a function $f(t) = \delta y_{\text{asymptotic}} + (\delta y_0 - \delta y_{\text{asymptotic}}) \times \exp(-t/\tau)$ to the measured data. The parameters are the initial mean shift, the mean shift which is expected asymptotically and the risetime. From the risetime and the natural polarization time constant τ_p the asymptotic polarization level can be calculated : $P = 92.4\% / (1 + \tau_d/\tau_p)$, and

Distributions for right and left circular polarized light

Figure 13: Distributions of scattered photons for linear and circular polarized light

$1/\tau = 1/\tau_d + 1/\tau_p$. For the measurement shown in fig.14 it has been estimated [30] : $\tau = 65 \pm 8$ min, $P_{asymptotic} = 19\% \pm 2.4\%$, $\delta y_{asymptotic} = 100 \pm 6\mu$, $P_{max} = 15.7 \pm 2\%$. In fig.14 all data points measured during an interval of 20 min do not match the curve. This observation is explained by a displacement of the distribution of the backscattered photons during this time. Due to the limited aperture the systematic effects discussed above change the mean shift, which was then compensated by changing the angle of the electron beam to recenter the distribution of the scattered photons.

Figure 14: Polarization build up at LEP

11 Energy Calibration at LEP

To perform an energy calibration a depolarizing magnetic field in the horizontal plane with an integral strength of 4.3 Gm is applied. The frequency is slowly changed from f_1 to f_2 . The frequency span is typically 112 Hz in 60-90 s corresponding to a spin tune range of 0.01 and an energy range of 4.4 MeV.

The polarization is measured at the same time and three different patterns are observed (see fig.15) [31] :

- The polarization level does not change.
- The polarization level decreases to zero or changes to the opposite direction.

- The polarization level decreases by a small amount.

Figure 15: Resonant Depolarization for Energy Calibration at LEP : The mean shift δy is shown as a function of time

If the depolarizer frequency sweep does not cover the resonance, the polarization is not affected. If the sweep covers a frequency where the resonance condition (see eq.3) is fulfilled, the polarization is totally destroyed or the direction is reversed.

In the vicinity of the main resonance synchrotron sidebands are expected due to the modulation of the energy with the synchrotron frequency. This is the case for a frequency $f_{depolarizer}/f_{rev} = \gamma a \pm Q_s$. A sweep over these resonances causes a partial depolarization of the beam. For each resonance two synchrotron sidebands are expected and they have been observed at LEP.

12 Conclusion for LEP

The polarization is measured with a statistical error of 1 % within about 1 min. After an optimization of the polarimeter the offset is less than 1 %. The absolute level of polarization is known to an accuracy of $\delta P/P = 10\%$. The energy is calibrated with an error of about 1 MeV. An energy calibration does not require more than a polarization level of more than 5 %, although with a higher level the calibration is much easier to do.

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