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First Observation of Transverse Beam Polarization in LEP

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Abstract

The results of beam polarization measurements performed in 1990 at the CERN Large Electron Positron storage ring (LEP) are reported. A significant asymmetry was observed in the Compton back-scattered photon distribution when illuminating the LEP electron beam with circularly polarized laser light. The corresponding polarization level is estimated to be $9.1\% \pm 0.3\%$ (statistical) $\pm 1.8\%$ (systematic). The validity of the polarization signal was assessed by varying the laser light polarization and by applying to the electron beam known depolarizing resonances. The measurement is consistent with the predicted polarization degree.

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1 Introduction

Beam polarization is a precious tool to study the properties of the Z boson [1]–[7]. In the large electron positron collider (LEP) at CERN, one has to rely on the natural build-up of transverse polarization by Sokolov-Ternov effect [8]. This effect has been observed and used in several storage rings [9] at lower energies. This process is very weak, 310 minutes rise time at 46 GeV beam energy in LEP, but could lead to a maximum polarization of 92.4%. Depolarizing effects related to unavoidable imperfections in the beam optics are, however, expected to be rather strong at these energies: first order predictions [10] range between 10 to 20% polarization, but higher order effects, which are very uncertain however, could reduce the polarization to unobservable level. Specific spin optimization procedures have been designed [11] that could improve the polarization to above 50%, but they require starting from an observable polarization degree. Given these uncertainties, the goal of the 1990 polarization experiments was to establish, as a starting point for further optimization, what degree of polarization can be achieved in LEP with only minor modifications.

Eight shifts of eight hours were dedicated to polarization studies in July and August 1990. Their purpose was to commission and gain experience with the polarimeter and to develop an optics on which the beam would naturally get polarized.

Positive results were obtained during a 24 hours run on the last day of the 1990 LEP running period granted to polarization studies by the LEP users community.

2 LEP Machine Configuration

Under physics conditions, several depolarizing sources (vertical orbit distortions and vertical dispersion, uncompensated solenoids, beam-beam effect,...) ensure that the beams remain unpolarized. This expectation was confirmed by parasitic observations with the polarimeter during physics runs.

A first and mandatory measure to weaken the depolarizing sources is to strip down the machine from all known electric or magnetic fields detrimental to the polarization mechanism. To this purpose several actions were taken:

- The following items were switched off: i) the experimental solenoids and their skew quadrupole compensators; ii) the electrostatic separators; iii) the arc skew quadrupoles; iv) the wiggler magnets, which require very good optics to help polarization.
- The RF frequency was changed from its operational value to the value corresponding to the "central orbit" [12].
- A detuned optics was adopted at the experimental insertions to reduce strong sources of vertical orbit distortion and dispersion.

- Only electrons were injected (the polarimeter is installed on the electron side) and the current was limited to $4 \times 140 \mu\text{A}$ to avoid beam instabilities.

First-order polarization calculations were performed using the computer programme SITF [13]. A small but measurable beam polarization should result from these conditions, given the expected machine imperfections and a good orbit correction [10], at well chosen values of beam energy, of the betatron tunes, Q_x and Q_y , and the synchrotron tune, Q_s .

The spin precession frequency, or spin tune ν_s , is directly related to the beam energy by the anomalous magnetic moment $\frac{g_e - 2}{2}$ of the electron:

$$\nu_s = \frac{g_e - 2}{2} \frac{E_{beam}}{m_e} = \frac{E_{beam}(\text{GeV})}{0.44065}$$

A beam energy of 45.64 GeV (the Z peak) corresponds to $\nu_s = 103.55$. The main resonances to be avoided are

- Integer resonances $\nu_s = n$;
- Betatron resonances $\nu_s = n_x \pm Q_x$ or $n_y \pm Q_y$;
- The synchrotron resonances: $\nu_s = n_s \pm Q_s$.

All resonances are strongly excited close to the 'systematic' integer resonances [14]

$$\nu_s = 8k \pm \text{int}[Q_{x/y}]. \quad (1)$$

The normal operating point of LEP in 1990 was $Q_x = 71.38$, $Q_y = 77.28$. The energy $E_{beam} = 46.5$ GeV, corresponding to $\nu_s = 105.55$, was chosen for polarization studies, as it avoids the vicinity of the systematic spin resonances. Furthermore, the closest betatron resonances were moved away by choosing smaller values of the fractional parts of the betatron tunes, $Q_x = 71.12$, $Q_y = 77.20$. This relatively large change of tunes could be done safely at nominal energy, although the beam had to cross strong synchro-betatron resonances. The synchrotron tune was unchanged.

The key to obtaining high polarization is to correct carefully the vertical closed orbit distortions, for, if they vanished, the polarization would reach 92 %. During normal operation, the residual vertical closed orbit distortions are corrected down to about 1 mm r.m.s., while the vertical dispersion D_y is measured to be then 20 to 25 cm r.m.s. This parasitic vertical dispersion excites the vertical betatron spin resonances, in proportion to D_y^4 , as well as synchrotron spin resonances of all orders, in proportion to D_y^2 and higher powers. The gain to be expected from lowering the vertical dispersion is thus very large.

For the polarization runs, the standard LEP orbit correction procedure MICADO was performed with particular care, using up to 60 orbit correctors and removing by hand faulty beam monitors from the orbit measurements. The procedure was rather lengthy, but a vertical orbit distortion of $\langle y \rangle = 0.53$ mm

r.m.s. was achieved. For this orbit, the vertical dispersion was measured to be only $\langle D_y \rangle = 13$ cm. This improvement of the orbit also decreased the vertical beam size.

With this decreased vertical dispersion and the other optical improvements, first order calculation predicted a polarization of 20% at the chosen energy, figure 1. It is expected that higher order effects would reduce this prediction by a factor of two or more [10].

To summarize, the working point for these polarization studies was

$$\nu_s = 105.55 \quad Q_x = 71.12 \quad Q_y = 77.20 \quad Q_s = 0.085$$

and the machine was in a normal, although simplified, configuration. Vertical orbit distortions were reduced by careful correction to $\langle y \rangle = 0.53$ mm r.m.s. and the vertical dispersion to $\langle D_y \rangle = 13$ cm r.m.s.

3 Polarization Measurement

The LEP polarimeter [16] [17], based on spin-dependent Compton scattering of circularly polarized photons from polarized particles [15], monitors the transverse polarization of the electron beam. A frequency-doubled Nd-YAG laser situated in the Optical Laboratory generates 12 ns long, ~ 50 mJ light pulses at a ~ 30 Hz repetition rate and wavelength of 532 nm. The light is guided over a distance of about 125 m to the Laser Interaction Region (LIR) and crosses the electron beam at an angle of 3 mrad. From the Compton interaction between the laser light and an e^- bunch, around 10^3 photons with an energy range of 0-28 GeV are backscattered in a cone of half aperture $\sim 1/\gamma$ around the direction of the incoming electrons. The transverse profile of the backscattered beam is recorded in a silicon strip detector, situated ~ 247 m downstream and protected by 2.5 radiation lengths of tungsten. A typical measured vertical γ -profile is shown in figure 2. The profile is approximately gaussian with a r.m.s. width of about 5 mm.

The angular distribution of the backscattered photons depends both on the polarization of the light and on that of the electron beam. The measurement of transverse polarization consists in measuring a shift $\Delta\langle Y \rangle$ of the center of gravity of the vertical profile when reversing the circular polarization of the light from $-\xi$ to $+\xi$:

$$\Delta\langle Y \rangle = \kappa \xi P_e \quad (2)$$

where κ is the analyzing power of the polarimeter and P_e the electron transverse polarization. Simulations of the polarimeter [18]–[21] for a beam energy of 46.5 GeV give $\kappa = 500 \pm 30 \mu\text{m}$.

For linearly polarized laser light the Compton scattering cross section does not depend on the beam polarization. A change of the orientation of the linear light

polarization from horizontal to vertical leads to a change in the shape of the γ -distribution (the width increases while the peak value decreases and vice versa) without any shift.

Given the small size of the expected shift ($2 \cdot 10^{-7}$ radians) it is crucial to reverse the polarization of the light without changing its geometrical properties. A flexible control of the light polarization is provided at the output of the laser by a setup described in figure 3. First, a polarizer provides linearly polarized light. Second, a continuously rotating half-wavelength retardation plate ($\lambda/2$) provides a rotation of the optical axis of the light by an amount that can be varied by an adjustable time delay Δt in the laser trigger. The laser is triggered every $1/8$ turn of this plate, so that the optical axis of the light is rotated by $\pi/2$ between each laser shot. Third, a quarter-wavelength retardation plate ($\lambda/4$) provides elliptical light. The transmitted light is linearly polarized if the optical axis of the incident light is at an angle of $n\pi/2$ with respect to that of the $\lambda/4$ plate. It is circularly polarized if this angle is $(2n + 1)\pi/4$. Depending on the value of Δt , a sequence of alternating right-handed circular (vertical linear) and left-handed circular (horizontal linear) polarizations is generated. Since each polarization state is produced by four different angular positions of the rotating plate, the effect of geometrical imperfections should largely cancel out. To provide a cross-check, a fourth element, a $\lambda/2$ plate, can be inserted in the laser beam, providing another helicity reversal. By comparing measurements with this additional plate 'IN' and 'OUT', any residual geometrical effect can be eliminated.

The light polarization at the interaction point is measured at the exit of the LIR section. In figure 4a) the variation of the degree of circular polarization was measured as a function of the angular position of the rotating plate, by varying Δt . The maximum amount of circular polarization was measured to be about 85 %. This reduction from almost perfect polarization is attributed to various depolarizing effects from elements in the transport line (reflections, birefringence etc.). A further rotation by 22.5° produces linearly polarized light and inserting the additional $\lambda/2$ plate reverses the pattern as expected.

4 Results

After optimization of the electron beam optics, the LIR was optimized to yield the maximum number of backscattered photons. Then polarization measurements were made, first varying the light polarization, then the machine conditions.

The data were taken as follows: the vertical profiles were accumulated separately for the alternating light polarizations over 2000 successive laser shots, and the averages and widths calculated. The number of backscattered photons associated with each data point is of the order of 10^6 . An estimate of the error on each measurement was estimated from the scatter of the 20 partial results based on 100 shots each. During the offline analysis data points were cut if they showed either missing laser pulses or rapid changes in the vertical or horizontal beam position during the 2000 laser shots.

The first experiment consisted in varying the light polarization. The change in peak height was measured as a function of the angular position of the rotating plate as shown in figure 4b). As expected, a zero crossing occurs for circular light and a maximum for linear light.

The variation of the centre of gravity shift $\Delta\langle Y \rangle$ as a function of the light polarization was recorded simultaneously, figure 4c): a shift of about $40 \mu\text{m}$ was detected when switching from left to right circular light; the shift vanished for linearly polarized light. This observation was first evidence for transverse beam polarization.

The detailed measurements of the vertical profile of backscattered photons are in agreement with these observations. We define the asymmetry $A(y)$:

$$A(y) = \frac{n_1(y) - n_2(y)}{n_1(y) + n_2(y)}$$

where $n_{1,2}(y)$ are the γ -rates at a vertical position y for right and left circular light, (or horizontal and vertical linear light). In figure 5 the measured asymmetries are shown, and compared with the expectations for circular and linear light, calculated for 100 % light and electron polarizations. For linear light the measurements are compatible with the simulation results. For circular light the measurement shows an asymmetry compatible with the simulation results for an electron transverse polarization of $\sim 10\%$.

The possibility that the shift of $40 \mu\text{m}$ be due to residual optical imperfections was investigated by inserting the additional $\lambda/2$ plate. The vertical shift was reversed (first points in figure 6). From these measurements and similar ones performed subsequently, it was deduced that a systematic vertical shift of $\pm 5 \mu\text{m}$ or less could be attributed to optical imperfections.

Although the previous measurements strongly suggest that polarization had indeed been observed, several machine optics manipulations were performed, aiming at depolarizing or repolarizing the beam by applying known sources of depolarization.

The data are shown on figure 6. They are divided in 9 periods of time according to different optics manipulations.

The polarization rise-time τ and the asymptotic level P_∞ are related to the depolarization time τ_d :

$$P_\infty = \frac{P_0}{1 + \tau_p/\tau_d} \quad (3)$$

$$\tau = \frac{\tau_p}{1 + \tau_p/\tau_d}, \quad (4)$$

where $P_0 = 0.924$ and $\tau_p = 310$ minutes are the ideal polarization degree and rise time due to the Sokolov-Ternov effect. The time evolution of the polarization is governed by the equation:

$$P(t) = P_\infty + (P_{init} - P_\infty)e^{-(t-t_{init})/\tau}$$

Period	$\chi^2/\text{D.F.}$ of the fit	$P_\infty(\text{fit})$ %	$P_\infty(\text{exp.})$	Conditions and comments
1	0.99	$9.1 \pm 0.3 \pm 1.2$	input	stable beam, asymptotic polarization
2	1.07	$5.1 \pm 0.6 \pm 1.6$	7.4	excitation of $\nu_s=106 \times 1$
3	0.74	$2.5 \pm 1.6 \pm 1.3$	0.3	excitation of $\nu_s=106 \times 5$
4	1.26	$11.5 \pm 3.1 \pm 2.1$	9.1	natural rise
5	4.4	$0.6 \pm 0.6 \pm 1.7$	2.1	RF trips, solenoid bumps ON
6	1.3	$1.9 \pm 0.7 \pm 1.2$	2.1	stable beam, solenoid bumps ON
7	2.36	$9.1 \pm 0.3 \pm 1.3$	9.1	asymptotic polarization
8	0.62	$2.0 \pm 0.6 \pm 1.2$	1.0	excitation of $\nu_s=106 \times 2.5$
9	2.4	$11.7 \pm 2.4 \pm 2.7$	9.1	natural rise

Table 1: Summary of fits to the polarization measurements. The first error is statistical, the second is systematic as described in the text. The theoretical expectations are also shown for comparison.

For each period the expected behaviour was calculated, given the approximately known depolarization applied. Alternatively, a one parameter fit to P_∞ could be performed to the data. Both calculations are shown in figure 6 and summarized in table 1. Beside statistical errors, the following systematic errors were considered: the possibility of a 5 microns systematic shift in $\Delta\langle Y \rangle$ (all periods); uncertainties in the transition time between consecutive conditions (periods 2,3,4,9); and scale factor for the goodness-of-fit (periods 5,7,9). In addition, an overall scale error of $\pm 15\%$ should be assigned to the results, due to the uncertainties in the polarimeter analysing power and in the light polarization.

The conditions in each period were as follows:

- Period 1: asymptotic polarization.

These measurements, taken in stable beam conditions, show a centre of gravity shift $\Delta\langle Y \rangle = 38.7 \mu\text{m}$. This is compatible with a stable, asymptotic polarization level of: $P_\infty = (9.1 \pm 0.3_{\text{stat.}} \pm 1.2_{\text{syst.}})\%$.

- Period 2: weak excitation of the spin resonance 106.

The harmonic spin matching procedures [11] [22], foreseen to optimize the polarization, can also be used to excite a spin resonance and to destroy the polarization. In period 2, the cosine component of the integer spin resonance 106 was excited. The vertical orbit bumps used for this purpose were limited to a maximum orbit excursion of 2 mm ($20 \mu\text{rad}$) to test the procedure. The corresponding depolarization time at $\nu_s = 105.55$ was calculated to be $\tau_d = 24$ minutes, corresponding to $P_\infty = 7.4\%$. The data are consistent with a decrease of the polarization to an asymptotic value of $P_\infty = (5.1 \pm 0.6_{\text{stat.}} \pm$

1.6_{syst.})%.

- Period 3: strong excitation of the spin resonance 106.

The strength of the bumps was increased to a maximum orbit excursion of about 10 mm (100 μ rad). The characteristic time of the depolarization is calculated to be $\tau_d = 1.0$ minutes for an asymptotic polarization level of $P_\infty = 0.3\%$. Again the data are consistent with this expectation, with a fitted value of $P_\infty = (2.5 \pm 1.6_{\text{stat.}} \pm 1.3_{\text{syst.}})\%$, but do not provide a conclusive demonstration.

- Period 4: natural polarization.

The bumps were then switched off. It was expected that the beam would repolarize with a time constant of 29.6 minutes or $P_\infty = 9.1\%$. The time constant which gives the best fit is $\tau = (37 \pm 10_{\text{stat.}} \pm 7_{\text{syst.}})$ minutes, which corresponds to an asymptotic polarization degree of $P_\infty = (11.5 \pm 3.1_{\text{stat.}} \pm 2.1_{\text{syst.}})\%$. Given the rather large statistical errors, this agrees with the expected behaviour.

- Periods 5 and 6: depolarization by the solenoid compensating bumps.

It was shown in [23] that small vertical orbit bumps can compensate the spin rotation generated by the experimental solenoids. These bumps were used to simulate the depolarizing effect of the solenoids (which were switched off during the measurements). Their calculated effect at $\nu_s = 105.55$ yields a depolarization time constant $\tau_d = 13$ minutes. The combination of the time constants gives decay time and asymptotic polarization level of $\tau = 9$ minutes, $P_\infty = 2.1\%$.

Period 5 was perturbed by vertical instabilities of the beam. An RF unit was found faulty. This may explain many doubtful points (negative polarization). At the end of period 6, the polarization settles at a level of $P_\infty = (1.9 \pm 0.7_{\text{stat.}} \pm 1.2_{\text{syst.}})\%$, consistent with the calculation.

- Period 7: asymptotic level.

The solenoid compensation bumps were then taken out, but the computer network broke down. The problem was repaired a few hours later [24]. When the polarization could be measured again it had recovered its asymptotic value of 9.1%.

- Period 8: depolarization by the spin resonance 106.

The excitation of the resonance was chosen such that the decay time of the polarization should be easily observed. Bumps amplitudes of 50 μ rad (around 5 mm) were selected to yield a resonance depolarization time of 3.8 min. The overall depolarization characteristic time and asymptotic polarization level should then be: $\tau = 3.3$ minutes $P_\infty = 1.0\%$. The data

clearly show a decrease of the polarization, to an asymptotic value of $P_{\infty} = (2.0 \pm 0.6_{\text{stat.}} \pm 1.2_{\text{syst.}})\%$.

- Period 9: natural polarization.

After suppression of the resonance excitation, the beam repolarized with a fitted characteristic time of $(38 \pm 8_{\text{stat.}} \pm 9_{\text{syst.}})$ minutes, corresponding to an asymptotic polarization level of $P_{\infty} = (11.7 \pm 2.4_{\text{stat.}} \pm 2.7_{\text{syst.}})\%$.

At this time the beam was lost due to an interlock and the experiment was terminated.

5 Conclusions

After careful set-up of LEP and elimination of known sources of depolarization, a signal consistent with observation of transverse polarization was seen.

It was verified that this signal was not created by optical defects in the laser Compton polarimeter. The polarimeter studies with linearly polarized light gave the expected results.

By applying known sources of depolarization the signal was significantly reduced and reappeared when switching them off. The pattern of changes are consistent with expectations.

Further and more precise experiments are presently prepared to confirm these first results. Resonant depolarization will be tried, to measure the LEP beam energy, as well as harmonic spin matching to improve the degree of polarization.

However, an important step was done: it was shown that the cures to the machine imperfections were sufficient to let a small degree of polarization to develop, providing the necessary starting point for further progress.

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Figure 1: Polarization on a realistic model of the LEP polarization optics

Figure 2: Measured vertical γ -distribution at the detector.

Figure 3: Sketch of the optical section at the laser output for the production and control of different light polarization states.

Figure 4: Observations related to the laser light polarization. The parameter is the time delay of the laser trigger, Δt , controlling the angular position of the $\lambda/2$ rotating plate.

- Degree of circular light polarization at the LIR.
- Change in the peak height in the vertical profile of backscattered photons.
- Centre-of-gravity shift $\Delta\langle Y \rangle$ of the vertical profile.

Figure 5: Simulated and measured asymmetries in the vertical profiles of backscattered photons.

Top left: simulated profile and asymmetry for linear light;

Bottom left: measured asymmetry for linear light;

Top right: simulated profile and asymmetry for circular light on 100% polarized electron beam;

Bottom right: measured asymmetry for circular light.

Figure 6: Experimental results in terms of mean shift $\Delta\langle Y \rangle$, related to the transverse polarization by Eq. (1). The experimental points indicated with an 'x' (negative $\Delta\langle Y \rangle$ values) represent measurements obtained with the push-pull half wave plate in 'IN' position.

Full line: results of the fit; dashed line: expected behaviour.