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HTML ABSTRACT

Spin Dynamics In LEP With 40-100 GeV Beams

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Abstract. Radiative spin polarization has been studied in the Large Electron-Positron Collider (LEP) at CERN for beam energies from 40 GeV to 100 GeV. The data cover a unique range of spin dynamics, not previously accessible with other storage rings. After optimization of machine parameters and the successful application of new Harmonic Spin Matching techniques, a transverse beam polarization of 57 % was obtained at 44.7 GeV. At 60.6 GeV the maximum level reached 8 %. The observed energy dependence of radiative spin polarization at LEP is in excellent agreement with the theoretically expected behavior. The LEP data provide the first experimental confirmation for a theory of depolarization at very high energies, first developed in the 1970s by Derbenev and Kontratenko. The results will help to guide the design of any future high energy electron-positron storage ring requiring polarized beams.

INTRODUCTION

The Large Electron-Positron collider (LEP) was operated at CERN between 1989 and 2000 [1]. As the largest storage ring to date LEP accelerated electron and positron beams from 22 GeV to more than 104 GeV [2]. The compensation of synchrotron radiation losses and the necessary beam stability were achieved with an accelerating radio-frequency voltage of up to 3.65 GV.

The lepton beams in LEP polarized spontaneously due to the Sokolov-Ternov effect [3]. We shortly review the main features of radiative spin-polarization for LEP, without going into any detail. For a planar storage ring the polarization builds up in the vertical transverse direction and (without imperfections) reaches an asymptotic degree of 92.4 %. The classical "spin vector" precesses around the vertical axis with a frequency f_{spin} that is a multiple ν of the particle revolution frequency f_{rev}. The number ν is called the spin tune and can be expressed as a simple function of the beam energy E:

$$\nu = \frac{E}{440.6486 \ \text{MeV}} \tag{1}$$

This relationship was used for a precise determination of the LEP beam energy [4]. The exponential build-up time τ_p of radiative polarization is a function of the storage

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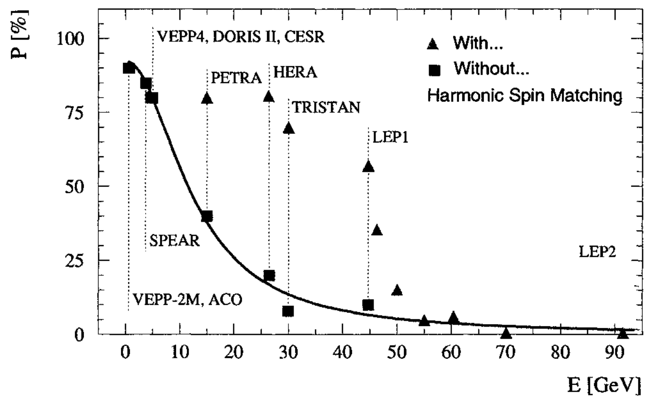

FIGURE 1. Overview of highest measured polarization degrees in electron-positron storage rings. Measurements with (triangle) and without (square) Harmonic Spin Matching are shown. The grey area indicates the energy range of the LEP collider.

ring bending radius and beam energy. Using LEP parameters we can write $\tau_p = 1/\lambda \approx (3.8 \cdot 10^{12}\mathrm{s}) \cdot (E/\mathrm{GeV})^{-5}$. λ is the polarizing rate. The polarizing time decreases rapidly with beam energy. For LEP at 100 GeV it is as small as 6 minutes, to be compared to 5.7 hours at 45 GeV.

Depolarization is caused by unavoidable imperfections in the vertical orbit of planar storage rings and is enhanced by synchrotron radiation. It is characterized by a depolarization time τ_d. The asymptotic degree P of polarization is reduced to

$$P = \frac{92.4\%}{1 + \tau_p / \tau_d} \tag{2}$$

and the "effective" build-up time is shorter ($1/\tau_p^{\mathrm{eff}} = 1/\tau_p + 1/\tau_d$). Polarization theories aim at estimating the term τ_p/τ_d. At LEP the behavior of polarization was studied in a unique range of high beam energies. Measurements at LEP and other lepton storage rings are summarized in Fig. 1. The LEP data cover a range from about 40 to 100 GeV that was not accessible with other storage rings. In this paper we describe and analyze the observed behavior of spin dynamics over this large range of beam energy.

OPTIMIZATION OF TRANSVERSE POLARIZATION

Careful optimization of the vertical orbit is required in order to maximize polarization at the beam energies of LEP. A good starting point for polarization was established with some basic machine optimization:

Precise control of the vertical orbit. Residual offsets after orbit correction were minimized with a yearly vertical realignment of all quadrupoles in LEP (~ 150 μm rms residual error after realignment). The knowledge of the beam offsets in the quadrupoles was improved by determining the alignment of the beam position monitors

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(BPMs) with respect to the magnetic centers of the quadrupoles. To that purpose a beam-based method was used ("k-modulation") with about 70 μm rms accuracy [5].

Accurate setting of spin tune (or beam energy). Depolarization is a resonant phenomenon. Spin resonances occur at spin tunes ν_{dep} that are the sum of an integer plus multiples of the machine tunes Q_x, Q_y and Q_s:

$$\nu_{depol} = k \pm k_x \cdot Q_x \pm k_y \cdot Q_y \pm k_s \cdot Q_s \quad , \quad k, k_x, k_y, k_s \in N \tag{3}$$

The machine tunes and the spin tune ν are set to values that maximize the distance of the spin tune to the most significant depolarizing resonances. Typically, ν is set close to a half-integer. Precise calibration of the beam energy at lower energies and its extrapolation with magnetic measurements [6] improves the accuracy in the setting of the optimized working point.

Optimization of the accelerator optics. The strength of magnets, the effect of imperfections on the beam and the efficiency of the orbit correction are functions of the accelerator optics. Polarization measurements at LEP were made with a variety of optics. Cell phase advances in the horizontal and vertical plane of 90/60, 90/90, 60/60 and 101/45 degrees were used, the later optics being the most favorable [7].

Even, if the spin tune is set to maximize the distance to the most important depolarizing resonances, residual depolarization will occur. It has been shown that the achievable polarization is mainly given by the strengths of the Fourier orbit harmonics (in spin precession frame) close to the spin tune [8]. For a spin tune ν=k+0.5, i=k,k+1 and some numerical factors γ_i the equilibrium polarization P can be written as:

$$P \approx \frac{92.4 \ \%}{1 + \sum_i \gamma_i a_i^2} \tag{4}$$

where the term a_i is the complex amplitude of the Fourier harmonic i of the vertical orbit. Relationship (4) opens the way to an efficient optimization of polarization. With vertical orbit bumps the amplitude of the orbit harmonics i can be reduced: $a_i \to a_i - a_i^{bump}$. This procedure is called "Harmonic Spin Matching" [8,9,10]. The method was improved at LEP by calculating the harmonics directly from the measured orbit. Such a deterministic correction is much less time consuming than empirical optimization. Fig. 2 shows an example of deterministic Harmonic Spin Matching. The method requires an accurate measurement of the vertical orbit, as discussed above.

A maximum polarization level of 57 % was achieved at 44.7 GeV with this method and in combination with empirical Harmonic Spin Matching. The measurement is shown in Fig. 3. During the experiment a rise-time measurement was performed on a separate bunch. This allows an accurate determination of the absolute polarization scale. The beneficial effect of Harmonic Spin Matching is shown in Fig. 1, where LEP measurements with and without Harmonic Spin Matching are shown.

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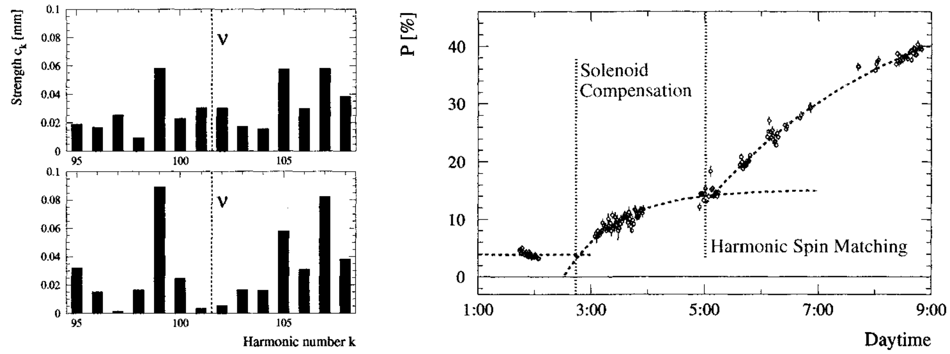


FIGURE 2. Measured strengths of harmonics before (left top) and after (left bottom) deterministic Harmonic Spin Matching. Measured beam polarization at 44.7 GeV on a selected bunch versus time (right). Solenoid spin compensation and deterministic Harmonic Spin Matching are indicated.

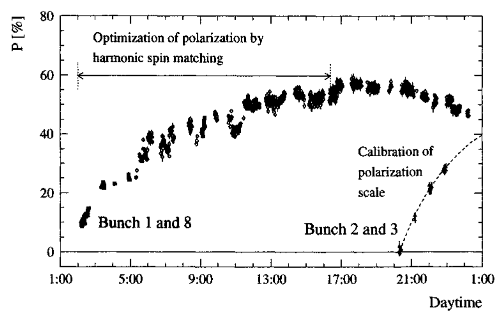
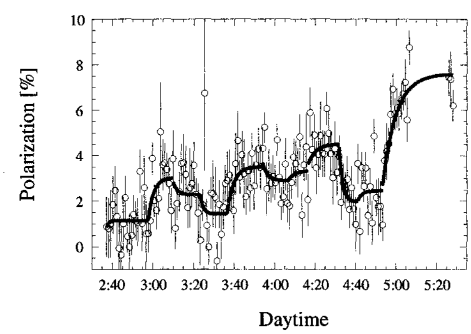


FIGURE 3. Measured LEP beam polarization on selected bunches versus time (at 44.7 GeV). The absolute scale of polarization was calibrated with an accurate measurement of the effective polarization build-up time.



	HSM bumps settings				Fit results
Time hr:min	137 (cos)	137 (sin)	138 (cos)	138 (sin)	P_1 (%)
02:35	0.0	0.0	0.0	0.0	1.15 ± 0.23
02:58	2.0	0.0	0.0	0.0	3.03 ± 0.37
03:10	2.0	0.0	2.0	0.0	2.28 ± 0.30
03:23	2.0	0.0	2.0	2.0	1.45 ± 0.27
03:36	2.0	2.0	2.0	0.0	3.51 ± 0.28
03:54	2.0	2.0	2.0	-2.0	2.88 ± 0.25
04:06	2.0	2.0	2.0	0.0	3.33 ± 0.40
04:16	4.0	2.0	2.0	0.0	4.53 ± 0.34
04:33	6.0	2.0	2.0	0.0	1.86 ± 0.27
04:41	3.0	4.0	2.0	0.0	2.66 ± 0.35
04:53	3.0	2.0	0.6	-0.6	7.69 ± 0.36

FIGURE 4. Example of educated Harmonic Spin Matching at 60.6 GeV. The closest orbit harmonics were changed in known steps and the polarization level was measured versus time (left). The data was used to fit the asymptotic polarization levels (right). The final measurement shows the polarization after compensating the fitted orbit harmonics.

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Another type of Harmonic Spin Matching was developed at LEP. Vertical orbit bumps (inducing orthogonal amplitudes a_i^{bump}) are changed in known steps for different harmonics i. For each step the asymptotic polarization level is fitted. With a minimum of five polarization measurements (for different a_i^{bump}) the unknown harmonics a_i of the vertical orbit and some residual depolarization $(\tau_p/\tau_d)_0$ can be determined:

$$P_{asym} = \frac{92.4\ \%}{1+\left(\tau_p/\tau_d\right)_0 + \sum_i \gamma_i \left(a_i - a_i^{bump}\right)^2} \tag{5}$$

An experiment at 60.6 GeV is shown in Fig. 4. The polarization level was measured versus time. Overlaid are polarization fits that were used to determine the asymptotic degree of polarization for each setting of harmonic spin bumps. The results from the first 10 measurements were included in a fit to determine the orbit harmonics. The last measurement in Fig. 4 shows the polarization with compensation of the fitted harmonics. The best polarization level at 60.6 GeV reached 7.7 %.

ENERGY DEPENDENCE OF POLARIZATION

The expected energy dependence of polarization is included in the theory for depolarization at ultra-high energies by Derbenev and Kondratenko [11]. We follow their approach. With $\nu^2\lambda/Q_s^3 << 1$ subsequent passings of spin resonances are correlated. Polarization can then be described with Equation 2 and:

$$\frac{\tau_p}{\tau_d} = \frac{11}{18}\ \nu^2 \sum_{k,m} \frac{\left|w_k\right|^2 \left\langle T_m^2 \right\rangle}{\left[\left(k-\nu-mQ_s\right)^2 - Q_s^2\right]^2} \tag{6}$$

Here, w_k is the complex strength of the spin resonance at integer k, ν is the spin tune averaged over the particle ensemble and m an integer giving the order of the synchrotron sideband resonance. Betatron spin resonances with the transverse tunes Q_x and Q_y do not appear. For high energy lepton storage rings they are much weaker than synchrotron resonances and can be neglected. For a given rms strength of imperfections the statistical average value of $|w_k|^2$ is proportional to the square of the beam energy (or spin tune): $|w_k|^2 \propto \nu^2$. Equation 6 contains a term T_m:

$$\left\langle T_m^2 \right\rangle = I_m\left(\frac{\sigma_\nu^2}{2\ Q_s^2}\right) \cdot \exp\left(-\frac{\sigma_\nu^2}{2\ Q_s^2}\right) \tag{7}$$

The I_m are the modified Bessel functions. As representative LEP parameters we use $|w_k|^2 = 2\times10^{-10} \cdot \nu^2$, $Q_s = 0.077$ and a spin tune spread $\sigma_\nu = 6.67\times10^{-6} \cdot \nu^2$. The actual values w_k depend on the distribution of vertical orbit offsets. The Q_s values used at LEP varied from 0.0625 to 0.11.

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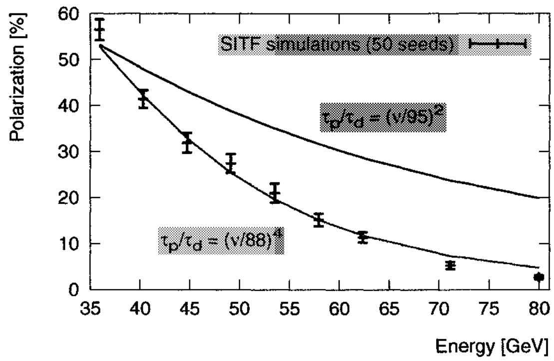

FIGURE 5. The simulated energy dependence of polarization is compared with curves that represent an increase of depolarization τ_p/τ_d with the second or fourth power of energy.

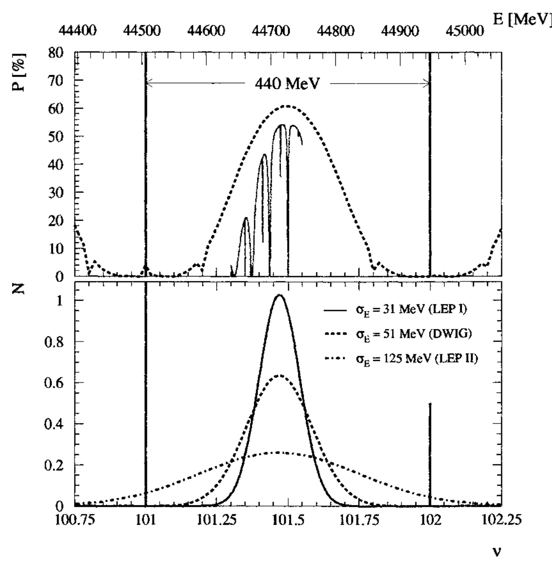

FIGURE 6. Illustration of depolarization enhancement at high beam energies. The upper graph shows a numerical simulation of LEP polarization versus beam energy around 44.7 GeV, both in linear (dashed) and higher order (solid) approximation. The spin resonances are clearly visible with the strongest contributions from $101+Q_s$ and $102-Q_s$. The lower graph shows the energy distribution in the beam. The narrow curve is for 44.7 GeV and corresponds to the simulation in the upper graph. The energy distribution becomes much wider if the damping wigglers (DWIG) are excited or the beam energy is increased (LEP II). As a result spin resonances are excited more strongly and polarization is suppressed.

The magnitude of the spin tune spread σ_v determines the size of the T_m term. Higher order spin resonances are not important and $\langle T_m^2 \rangle \cong 1$, if the spin tune spread is much smaller than the synchrotron tune. The achievable polarization level is then only affected by linear spin resonances ($v_{dep} = k \pm Q_s$). In the following this is called the "linear" theory. Polarization is expected to drop with the fourth power of beam energy (for

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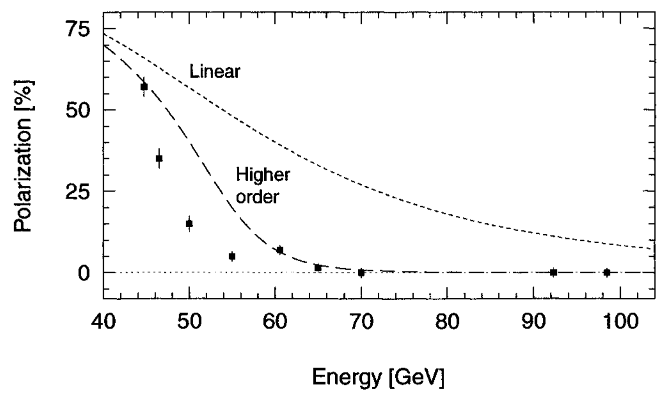

FIGURE 7. Maximum polarization levels measured for different energies in LEP. Note that the measurements at 44.7 GeV and 60.6 GeV were fully optimized. Measurements at other energies below 60.6 GeV were used for energy calibration purposes and are only partially optimized. The theoretically expected energy dependence of polarization is shown with $|w_k|^2 = 2\times10^{-10} \cdot \nu^2$ for both linear and higher order theory.

the same rms imperfections). This basic result from linear theory is compared in Fig. 5 with a numerical simulation, finding good agreement.

If the spin tune spread becomes larger than the synchrotron tune, the linear and higher order synchrotron resonances ($\nu_{dep} = k \pm k_s{\cdot}Q_s$, $k_s \geq 1$) limit the achievable polarization. This is referred to as "higher-order theory". Polarization drops even faster with beam energy than in the linear regime. An intuitive picture why depolarization is so strongly enhanced is shown in Fig. 6. As the spin tune spread becomes much larger at the high beam energies of LEP2, it does not only overlap higher order resonances, but also the strong linear and integer spin resonances.

The maximum levels of transverse polarization observed at LEP are shown in Fig. 7 for different beam energies. The measurement at 44.7 GeV is extrapolated to higher beam energies with Equations 6 and 7, assuming the same residual imperfections in the vertical orbit. Because we assume the same resonance strength $|w_k|^2 = 2\times10^{-10} \cdot \nu^2$ for the calculation of both the linear and higher order theory, the linear value is always above the higher order prediction. Experimentally a sharp drop in radiative spin polarization is observed at LEP, in good agreement with the expectation from higher order theory. In particular the measurement at 60.6 GeV is in excellent agreement with the theory. Measurements between 44.7 GeV and 60.6 GeV are below the expectation because they were not fully optimized.

The decrease in polarization is mainly due to the enhancement of depolarization from higher-order synchrotron resonances. It is much steeper than with the fourth power of energy that one would expect in linear theory. The LEP measurements are the first experimental confirmation of the theory that Derbenev and Kontratenko developed in the 1970s.

Above 70 GeV the condition $\nu^2\lambda/Q_s^3 << 1$ is violated for LEP parameters and the spin dynamics enters into the regime of uncorrelated passings of spin resonances [11].

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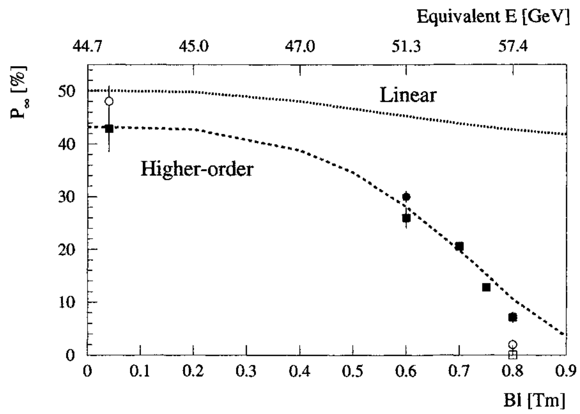

FIGURE 8. Observed polarization level at 44.7 GeV for different excitations Bl of the LEP damping wigglers. The upper scale indicates the beam energy that would produce the same spin tune spread. The polarization measurements are compared to the expectations from linear and higher-order theory.

Equations 6 and 7 no longer apply. Derbenev and Kontratenko have also studied this regime of spin dynamics [11] but it is beyond the scope of this paper to review the details of this theory. LEP is the first storage ring that operated in this special regime of spin dynamics. Measurements of polarization were performed at LEP up to 98.5 GeV. The data is shown in Fig. 7. No polarization was observed above 65 GeV. A hypothetical increase of polarization with beam energy for very intense synchrotron radiation [11,12] was not seen and would only be expected for LEP with a beam energy around 200 GeV.

The theory of Derbenev and Kontratenko was confirmed independently with the asymmetric damping wigglers in LEP. Those wigglers decrease the polarization build-up time but at the same time increase the spin tune spread. From Equation 7 we do then expect an increase of depolarization. The asymmetric wigglers therefore allow "simulating" the increased energy and spin tune spread at higher beam energies. The vertical orbit and other parameters can be kept conveniently stable. In Fig. 8 the measured polarization and the theoretical prediction are compared for different settings of the damping wigglers. Strong depolarization was observed for large excitations of the wigglers, in excellent agreement with the theoretical expectation.

POLARIZATION WITH COLLIDING BEAMS AT 45 GEV

Polarized beams in LEP were used for accurate energy calibration by resonant depolarization. The description of this method and its results for LEP are published in [4]. Originally it was foreseen to directly exploit the particle physics potential of polarized beams in LEP. In order to propose and implement such an option, it had to be shown that the transverse polarization can be rotated into the longitudinal direction in the interaction points of LEP and that polarization is preserved during collision. An appropriate spin rotator for LEP was designed and its performance was demonstrated in simulations [13].

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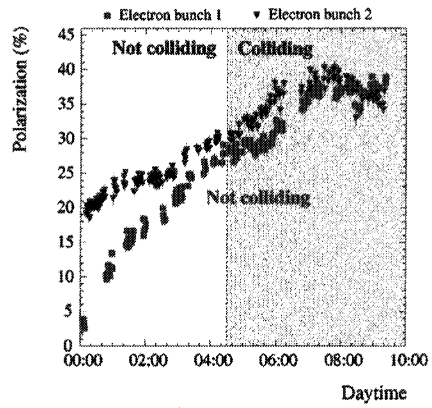

FIGURE 9. Polarization measurements during a beam-beam experiment. Electron bunch 1 (square) was not colliding during the whole experiment. Electron bunch 2 (triangle) was initially not colliding and was put into collision at 4:30h with a vertical beam-beam parameter of 0.04.

The strength of depolarization induced by beam-beam collisions was measured at 45 GeV. The measurements are shown in Fig. 9. The polarization of two electron bunches was monitored simultaneously. Polarization was slowly building up on both bunches while the vertical orbit was optimized for maximum asymptotic polarization. For the first part of the experiment both bunches were not colliding with the positron beam. At a time when both bunches had a similar level of polarization, one bunch was put into collision with a positron bunch. The measured vertical beam-beam parameter was 0.04. The polarization on both electron bunches kept increasing until it reached an asymptotic value of 38 %. As seen from Fig. 9, the difference in absolute polarization level between the colliding and the non-colliding electron bunch was smaller than 4 %. The beam-beam induced depolarization τ_p/τ_d was smaller than 0.3, imposing a "beam-beam" polarization limit of above 70 % for LEP with one collision point. Depolarization due to beam-beam effects is not a serious problem in a 45 GeV storage ring with LEP parameters. Collisions of polarized beams were, however, incompatible with the existing LEP experiments, and this option was finally abandoned.

CONCLUSION

Radiative spin polarization has been studied at LEP for beam energies from 40 GeV to 100 GeV. The data covers a unique range of spin dynamics, not previously accessible with other storage rings. After careful optimization of machine parameters and the successful use of new implementations of Harmonic Spin Matching, transverse beam polarization of 57 % was observed at 44.7 GeV. At 60.6 GeV the highest level reached 8 %. The observed energy dependence of radiative spin polarization in LEP is in excellent agreement with the theoretically expected behavior. The LEP data provide the first experimental confirmation for a theory of depolarization at very high energies, first developed in the 1970s by Derbenev and Kontratenko. With colliding beams at one interaction point, polarization levels of 38 % were observed. The experiment

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showed that beam-beam depolarization is weak for a 45 GeV storage ring with LEP parameters. The LEP results on polarization verify long standing theories and will help to guide the design of any future high energy electron-positron storage ring requiring polarized beams.

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REFERENCES

1. S. Myers. CERN Yellow Report 91-08.
2. G. Arduini et al. "LEP Operation and Performance with 100-GeV Colliding Beams". CERN-SL-2000-045-OP, Jun 2000. EPAC2000.
3. A.A. Sokolov and I.M. Ternov, "On Polarization and Spin Effects in the Theory of Synchrotron Radiation", *Sov. Phys. Dokl.* 8(1964)1203.
4. L. Arnaudon et al, "Accurate Determination of the LEP Beam Energy by Resonant Depolarization". *Z. Phys.* C66(1995)45-62.
5. B. Dehning et al., "Dynamic Beam Based Calibration of Beam Position Monitors". CERN SL/98-38-BI. EPAC98.
6. R. Assmann et al., "Calibration of centre-of-mass energies at LEP1 for precise measurements of Z properties". *Eur. Phys. J.* C 6(1999), 187-223.
7. R. Assmann and A. Verdier, "An Optics with 101/45 Degree Phase Advance for LEP". SL-Note-2000-013 OP.
8. V.N. Baier and Yu.F. Orlov, "Quantum Depolarization of Electrons in a Magnetic Field". *Sov. Phys. Dokl.* 10(1966)1145.
9. R. Rossmanith and R. Schmidt, "Compensation of Depolarizing Effects in Electron Positron Storage Rings". *Nucl. Instr. Meth.* A236(1985)231.
10. D.P. Barber et al, "High Spin Polarization at the HERA Storage Ring". *Nucl. Instr.Meth.* A338(1994)166-184.
11. Ya.S. Derbenev, A.M. Kondratenko and A.N. Skrinsky, "Radiative Polarization at Ultra-High Energies". *Part. Acc.* 1979, Vol. 9, pp. 247-266.
12. R. Assmann. "The regimes of polarization in a high energy e+e- storage ring". PAC99.
13. H. Grote, "Spin rotator". 2nd Workshop on LEP performance, Chamonix, France, 19-25 Jan. 1992. Ed. by J. Poole. CERN, Geneva, 1992. CERN SL 92-29 DI.

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